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Suspended sediment yield from glacier basins

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Abstract An analysis of suspended sediment and discharge yield, and catchment characteristics from a sample of 90 glacier basins is presented. The suspended sediment yield per unit area for all but one of the sample basins exceeds the global average as defined by Walling & Kleo (1979). There is no significant relationship between specific suspended sediment yield and either basin or glacier area, but yield does decrease with distance of the monitoring site from the glacier and with Borland's (1961) lambda, both surrogates for availability of areas of sediment storage. Basins containing predominantly warm-based glaciers produce higher suspended sediment yields than those containing predominantly cold-based glaciers. Within the group of basins containing warm-based glaciers, Icelandic basins, whose glaciers are also subject to recent volcanic activity, produce some of the highest suspended sediment yields per unit basin area.

INTRODUCTION

Meltwater draining from glacier basins transports high suspended sediment loads (Gurnell, 1987; Lawler *et al.*, 1992) which present major problems for the management and use of the meltwater (Bezinge *et al.*, 1989; Bogen, 1989). The estimation and prediction of sediment transport from glacier basins is, therefore, of major management importance. It also has geomorphological significance for understanding the denudation systems of glaciated areas, estimating landscape denudation rates, and comprehending the impact that the sediment and discharge regimes of glacier-fed rivers have on the dynamics and morphology of proglacial rivers (e.g. Fenn & Gurnell, 1987; Maizels, 1983).

Gurnell (1987) presented an analysis of suspended sediment and discharge yield information in relation to the catchment characteristics of 43 glacier basins. As a context to that analysis she stressed that many glacier basins could not be included because their suspended sediment transport and discharge records were too short (at least one full ablation season of information was required for comparative purposes) and that the variability and sometimes very crude quality of the suspended sediment concentration estimation procedures and sampling frameworks for those basins which were included could not be over-stressed. This paper builds on that analysis by investigating information from a larger sample of glacier basins. Sources of this additional data include Bogen (1989), Fountain (1992), Hardy (personal communication), Hicks *et al.* (1990), Hodgkins (1994), Hodson (1994), Kostrezewski *et al.* (1989), Lawler (1991, 1994), Lawler *et al.* (1992), Pálsson & Vigfrisson (1991), Raymond *et al.* (1995), Repp (1988), Rist (1990) and Tómasson (1991). As in the previous analysis, information on catchment characteristics of glacier basins was often incomplete and, in particular, identification of the underlying rock type (a potentially key variable in controlling susceptibility to glacial erosion, the consequent denudation of the catchment and the delivery of sediment) was rarely possible. However, some data were obtained for a total of 90 basins, of which 73 basins presented a good range of discharge, suspended sediment and catchment characteristic values.

VARIABILITY IN SUSPENDED SEDIMENT YIELD FROM GLACIER BASINS

The monitoring techniques and sampling frameworks used to investigate sediment transport in proglacial rivers can have very significant effects on the estimates of sediment yield that are produced (e.g. Gurnell *et al.*, 1992). Against the background of the significance of field monitoring techniques, the variability in sediment yield from a sample of four glacier basins located within one small area of Switzerland (Bas Glacier d'Arolla, Haut Glacier d'Arolla, Glacier de Ferpècle and Glacier de Tsidjiore Nouve) and assessed by similar monitoring approaches, has recently been presented (Gurnell, 1995). Comparative information from these basins at a variety of timescales was used to illustrate the enormous variability in sediment yield that can occur within one small area, and to suggest potential controlling factors. Of particular relevance to the present discussion was that even with a standardized method of assessing sediment yield, there were major contrasts in mean annual suspended sediment yields between basins: 1800 (10 years of record), 1100 (10 years), 3000 (2 years), 280 (1 year) t km^{-2} $year^{-1}$ for the Tsidjiore Nouve, Bas Arolla, Haut Arolla and Ferpècle basins, respectively. This variability was attributed to contrasts in a number of factors including underlying rock type and subglacial deposits, rates of glacier movement, character of the glacier drainage system, and the topography of the basins. For the basins with 10 years of estimates of annual suspended sediment yield, the ratios of the highest to lowest annual suspended sediment yield were 3.6 and 13.4 for the Tsidjiore Nouve and Bas Arolla basins, respectively. Thus suspended sediment yield varies greatly over small distances in space and over short periods of time.

With this variability in mind, the remainder of this paper attempts a statistical analysis of annual discharge and suspended sediment yield in relation to catchment characteristics from up to 90 glacier basins distributed latitudinally from New Zealand to Svalbard, representing warm-based, polythermal, and cold-based glacier systems.

SUSPENDED SEDIMENT YIELD FROM GLACIER BASINS – A GLOBAL PERSPECTIVE

The 90 glacier basins considered here have widely varying record lengths upon which mean annual suspended sediment yield estimates are based (ranging from 1 to 82 years, but with the majority of basins having less than 20 years of record). Table 1 describes the range in mean annual suspended sediment yield and discharge estimates and in the catchment characteristics of these basins.

The data are presented graphically in Figs 1-4. The same symbols are used in all graphs and are described in the underline to Fig. 1. The catchments have been split, according to the likely temperature regime of the ice, into three groups: those containing

Table 1 Range in catchment characteristics and in mean annual suspended yield and discharge from the sample glacier basins (values expressed to three significant figures).

Variable	Minimum	Maximum	Average	Median	*n*
Mean annual suspended sediment yield (10^6 t year^{-1})	3.0 E-6	63	4.36	0.085	90
Mean suspended sediment concentration (mg l^{-1})	56	7800	1330	975	72
Discharge volume (10^6 m^3 year^{-1})	0.816	83 000	3590	503	72
Runoff (mm year^{-1})	243	11 500	2240	1360	72
Catchment area (km^2)	2.1	294 000	7990	119	74
% Glacier cover	1	95	43	40	90
Relief (m)	560	5800	2090	1500	50
Distance of sediment monitoring site from glacier (km)	0.01	644	57.7	1.5	57

alpine or predominantly warm-based glaciers; Icelandic basins, which are also warm-based but are additionally influenced by recent volcanic activity (Björnsson, 1988); and those containing predominantly cold-based glaciers. The latter group was subdivided into two. Alaskan basins formed quite a large group which had predominantly larger catchment areas than the remaining, more widely geographically distributed, arctic basins. Catchments with less than a 10% glacier cover are also indicated in Figs 1-4.

Figure 1 demonstrates a five orders of magnitude range in the mean annual suspended sediment yield and discharge from the sample basins. This variability is reassuringly large in comparison with the likely interannual variability and thus bias in the average values for different record lengths for individual basins. Some of this wide range simply reflects differences in the catchment area of the basins and so Fig. 2 attempts to standardize for this by plotting suspended sediment yields in units of t km^{-2} year^{-1} and discharge in mm depth. Figure 2 illustrates the relatively low yields of suspended sediment and meltwater from the predominantly cold-based glacier basins, the higher yields from the warm-based glacier basins, with the Icelandic basins plotting within the zone of the highest observed yields.

Walling & Kleo (1979) reviewed estimates of suspended sediment yield for 1246 basins worldwide. They found a decrease in suspended sediment yield per unit area with increasing basin size, which is echoed in the upper envelope of the data plotted in Fig. 3. More significant in the present context is that all the basins, apart from one which contains a cold-based glacier, plot above the global relationship between suspended sediment yield per unit area and catchment area that was derived by Walling & Kleo (1979). Thus, Fig. 3 illustrates that these glacier basins have high suspended sediment yields in a global context, and that within the sample, basins with predominantly cold-based glaciers yield less suspended sediment than basins with predominantly warm-based glaciers. Furthermore, some of the highest sediment yields come from the Icelandic basins. Borland (1961) derived an index (λ) that could be employed in estimating sediment yield from glacier basins in Alaska:

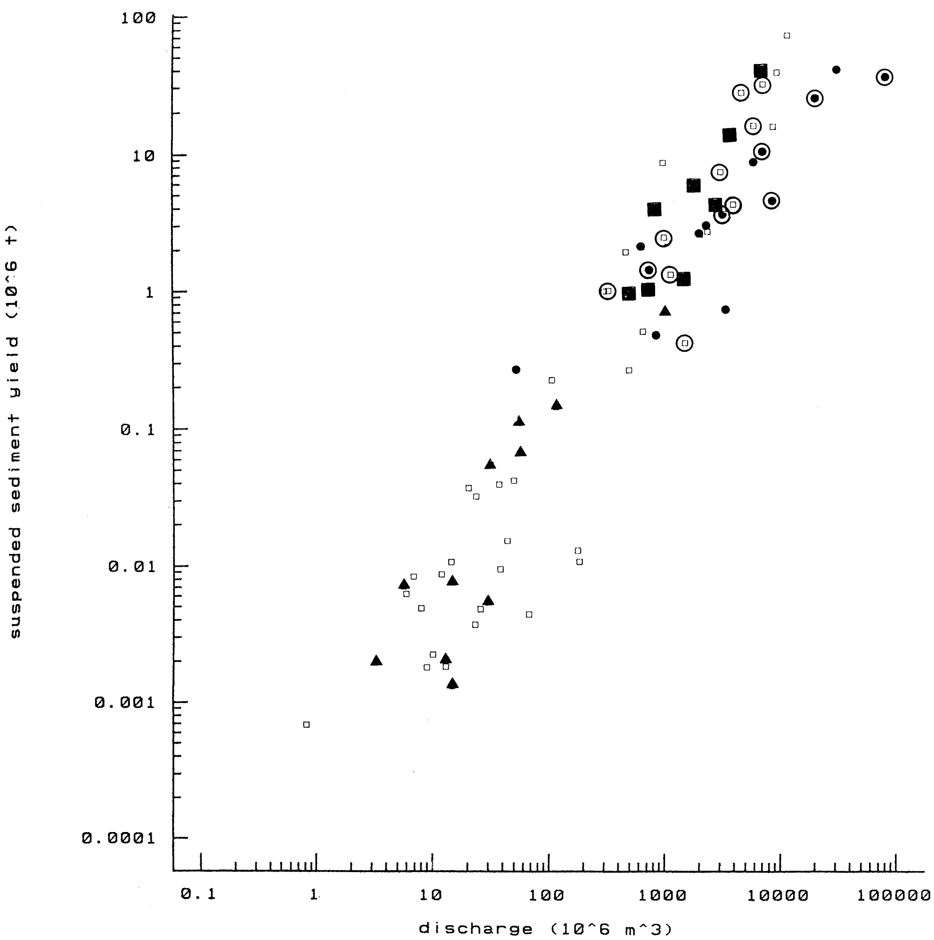

Fig. 1 The relationship between mean annual total suspended sediment yield and total discharge volume. In Figs 1-4, small open squares represent basins containing predominantly warm-based glaciers; large solid squares represent Icelandic basins; solid circles represent Alaskan basins; solid triangles represent other basins containing predominantly cold-based glaciers; any of these symbols contained within an open circle have a glacier cover which is less than 10% of the total basin area.

$$\lambda = (A_T L_G / A_G) \tag{1}$$

where A_T is the total catchment area, A_G is the glaciated area of the catchment and L_G is the length of river between the glacier snout and the monitoring site. Later work by Guymon (1974) found that the index was unreliable and could be improved by including information on the size of the transported sediment. However, estimates of λ are plotted in Fig. 4 because it represents an integrative index of the size of a major sediment source area (A_G) and the opportunities available for sediment storage (A_T and L_G) and because particle size information was not available for the present sample of catchments. Figure 4 indicates that although there is a reasonably well-defined negative trend in the

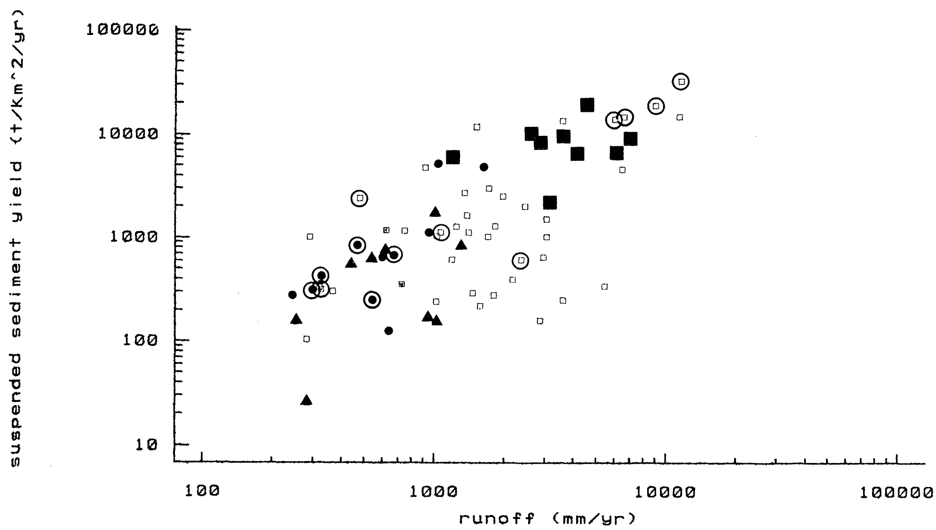

Fig. 2 The relationship between mean annual suspended sediment yield per unit area and runoff depth.

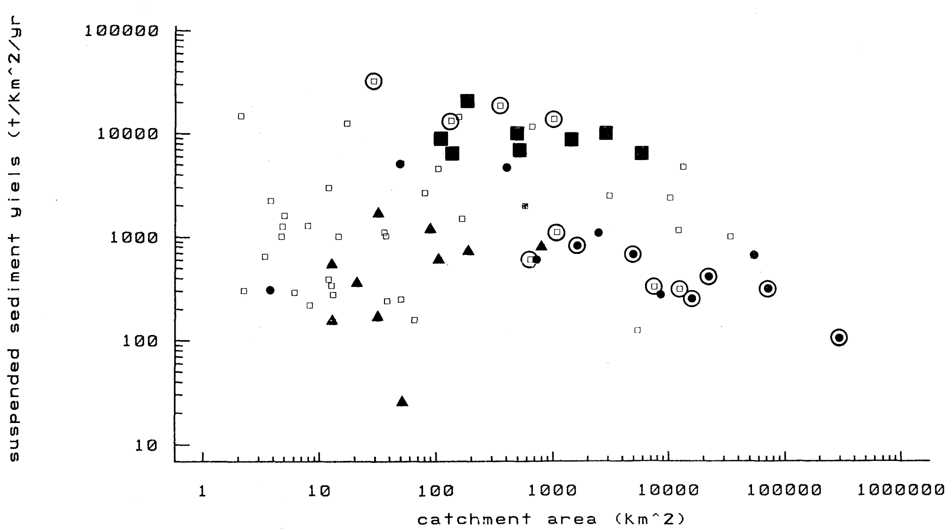

Fig. 3 The relationship between mean annual suspended sediment yield per unit area and catchment area.

data for Alaskan glaciers, this is not found in the data from other groups of glacier basins.

Simple and multiple regression models were employed to describe the relationship between $\log_{10}$ suspended sediment yield (total – SSY_T; per unit area – SSY) and one or more $\log_{10}$ transformed explanatory variables using the data from the sample of glacier basins. Table 2 lists only those models with slope parameters that were significantly different from zero ($P < 0.05$). No significant relationship was found

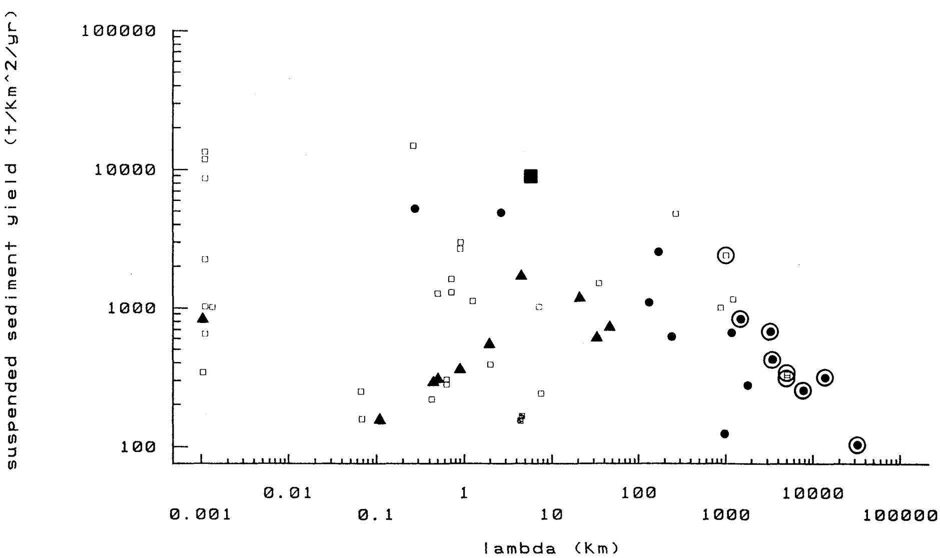

Fig. 4 The relationship between mean annual suspended sediment yield per unit area and the λ index derived by Borland (1961).

Table 2 Estimated regression relationships between suspended sediment yield, discharge and some catchment characteristics.

$\log_{10} SSY_T = -4.462 + 1.167 \log_{10} Q_T$	$r^2 = 0.893$	$n = 72$
$\log_{10} SSY = -0.186 + 1.046 \log_{10} Q$	$r^2 = 0.442$	$n = 72$
$\log_{10} SSY = 2.969 - 0.077 \log_{10} \lambda$	$r^2 = 0.076$	$n = 57$
$\log_{10} SSY = 2.933 - 0.094 \log_{10} L_G$	$r^2 = 0.074$	$n = 57$
$\log_{10} SSY = -1.220 + 0.565 \log_{10} R + 0.754 \log_{10} Q$	$R^2 = 0.242$	$n = 49$
$\log_{10} SSY = 3.209 - 0.652$ cold $+ 0.677$ Iceland $- 0.129$ Alaska $\log_{10} A_T$	$R^2 = 0.308$	$n = 74$
$\log_{10} SSY = 3.201 - 0.644$ cold $+ 0.685$ Iceland $- 0.166$ Alaska $\log_{10} A_G$	$R^2 = 0.299$	$n = 74$
$\log_{10} SSY = 0.157 + 0.499$ Iceland $+ 0.916 \log_{10} Q$	$R^2 = 0.489$	$n = 72$
$\log_{10} SSY = 3.086 - 0.414$ cold $- 0.220$ Alaska $\log_{10} L_G$	$R^2 = 0.145$	$n = 57$

Only regression relationships whose slope coefficients are significantly different from zero ($P < 0.05$) are included.

SSY_T – suspended sediment yield in t year^{-1}; Q_T – discharge volume in m^3 year^{-1}; SSY – suspended sediment yield in t km^2 year^{-1}; Q – discharge in mm year^{-1}; A_T – total catchment area in km^2; A_G – total glacier area in km^2; L_G – distance from glacier snout to monitoring site in km; R – relief from monitoring site to highest point on watershed in m; λ – for definition see text.

The following dummy variables take on the value 1 for basins within their group and zero for other basins:

cold – basins containing predominantly cold-based glaciers; Alaska – Alaskan glacier basins; Iceland – Icelandic glacier basins.

between SSY (suspended sediment yield per unit area) and A_T or A_G. However, SSY was found to be positively related to Q (discharge depth, in mm) and negatively related to λ and L_G, both surrogates for availability of sediment storage areas within the basin. SSY was also positively related to R (basin relief) as a second explanatory variable in combination with Q.

Four significant dummy variable regression models (Table 2) show contrasts in the response of $\log_{10}$ SSY to variations in specific $\log_{10}$ transformed explanatory variables between the different glacier types. The dummy variables "cold", "Alaska" and "Iceland" take on the value of 1 when basins from those areas are considered and otherwise take the value of zero. The base model (when none of the dummy variables take the value of one) relates to the response of warm-based glaciers. The models with A_T and A_G as explanatory variables show that the "Iceland", "warm" and "cold" groups represent a decreasing sequence in SSY with no trend relating to catchment or glacier size, whereas the "Alaska" group shows a decrease in SSY with an increase in either A_T or A_G. The trend of increasing SSY with Q has a higher intercept, but the same slope for the "Iceland" group in comparison with the other three groups. SSY decreases with increasing L_G for the "Alaska" group, but for other groups there is no such trend, simply a lower SSY for the "cold" group than for the remaining basins.

CONCLUSIONS

Given the inherent variability in suspended sediment yield from glacier basins, the enormous variability in the length of record and in the sampling techniques used to estimate annual suspended sediment yields, and the lack of information on some key explanatory variables, it is hardly surprising that strong relationships have not been found between SSY and other characteristics of the 90 glacier basins investigated in this paper. Nevertheless, a number of conclusions can be drawn from the above analyses:

(a) The variability in SSY_T between the sample of basins investigated is large in comparison with the inter-annual variability identified within 10 years of yield estimates for two alpine glacier basins studied by one of the present authors.

(b) SSY for all but one of the sample of basins exceeds the global average based on catchment area that was defined by Walling & Kleo (1979), indicating that glaciers form important sources of suspended sediment. Since glacier basins are increasingly being recognized as generators of relatively high bed load yields (e.g. Bogen, 1989; Gurnell, 1995; Hammer & Smith, 1983), the differences in total sediment yield between glacial and non-glacial basins are likely to be even greater.

(c) Significant relationships exist between SSY and both discharge (Q) and some catchment characteristics (λ, L_G and R) for the sample of basins.

(d) There are differences in response between basins containing different types of glacier. In particular, basins containing predominantly cold-based glaciers yield less suspended sediment than those containing predominantly warm-based glaciers. Icelandic basins have sediment yields that plot within the upper range of the basins containing warm-based glaciers.

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REFERENCES

Bezinge, A., Clark, M. J., Gurnell, A. M. & Warburton, J. (1989) The management of sediment transported by glacial meltwater streams and its significance for the estimation of sediment yield. *Ann. Glaciol.* **13**, 1-5.

Björnsson, H. (1988) Hydrology of ice caps in volcanic regions. *Society Science Islandica* **XLV**, 1.

Bogen, J. (1989) Glacial sediment production and development of hydro-electric power in glacierized areas. *Ann. Glaciol.* **13**, 6-11.

Borland, W. M. (1961) Sediment transport of glacier fed streams in Alaska. *J. Geophys. Res.* **66**, 3347-3350.

Fenn, C. R. & Gurnell, A. M. (1987) Proglacial channel processes. In: *Glaciofluvial Sediment Transfer: An Alpine Perspective* (ed. by A. M. Gurnell & M. J. Clark), 423-472. Wiley, Chichester, UK.

Fountain, A. G. (1992) Subglacial water flow inferred from stream measurement of South Cascade Glacier, Washington, USA. *J. Glaciol.* **138**(125), 113-119.

Gurnell, A. M. (1987) Suspended sediment. In: *Glaciofluvial Sediment Transfer: An Alpine Perspective* (ed. by A. M. Gurnell & M. J. Clark), 305-354. Wiley, Chichester, UK.

Gurnell, A. M. (1995) Sediment yield from alpine glacier basins. In: *Sediment and Water Quality in River Catchments* (ed. by I. D. L. Foster, A. M. Gurnell & B. W. Webb), 407-435. Wiley, Chichester, UK.

Gurnell, A. M., Clark, M. J., Hill, C. T. & Greenhalgh, J. (1992) Reliability and representativeness of a suspended sediment concentration monitoring programme for a remote alpine proglacial river. In: *Erosion and Sediment Transport Monitoring Programmes in River Basins* (ed. by J. Bogen, D. E. Walling & T. Day) (Proc. Oslo Symp., August 1992), 191-208. IAHS Publ. no. 210.

Gurnell, A. M. & Fenn, C. R. (1987) Proglacial channel processes. In: *Glaciofluvial Sediment Transfer: An Alpine Perspective* (ed. by A. M. Gurnell & M. J. Clark), 423-472. Wiley, Chichester, UK.

Guymon, G. L. (1974) Regional sediment yield analysis of Alaska streams. *J. Hydraul. Div. ASCE* **100**, 41-51.

Hammer, K. M. & Smith, N. D. (1983) Sediment production and transport in a proglacial stream, Hilda Glacier, Alberta, Canada. *Boreas* **12**, 91-106.

Hicks, D. M., McSavaney, M. J. & Chinn, T. J. H. (1990) Sedimentation in proglacial Ivory Lake, Southern Alps, New Zealand. *Arctic and Alpine Res.* **22**, 26-42.

Hodgkins, R. (1994) The seasonal evolution of meltwater discharge, quality and routing at a High-Arctic Glacier. Unpublished PhD thesis, Scott Polar Research Institute, University of Cambridge, UK.

Hodson, A. (1994) Climate, hydrology and sediment transfer process interactions in a sub-polar basin, Svalbard. Unpublished PhD thesis, University of Southampton, UK.

Humphrey, N. F. & Raymond, C. F. (1994) Hydrology, erosion and sediment production in a surging glacier; Variegated Glacier, Alaska, 1982-83. *J. Glaciol.* **40**, 539-552.

Kostrzewski, A., Kaniecki, A., Kapuściński, Klimczak, R., Stach, A. & Zwoliński, Z. (1989) The dynamics and rate of denudation of glaciated and non-glaciated catchments, Central Spitsbergen. *Polish Polar Res.* **10**, 317-367.

Lawler, D. M. (1991) Sediment and solute yield from the Jökulsá á Sólheimasandi glacierized river basin, Southern Iceland. In: *Environmental Change in Iceland: Past and Present* (ed. by J. K. Maizels & C. Caseldine), 303-332. Kluwer Academic Publishers, The Netherlands.

Lawler, D. M. (1994) Recent changes in rates of suspended sediment transport in the Jökulsá á Sólheimasandi glacier river, Southern Iceland. In: *Variability in stream erosion and sediment transport* (ed. by L. J. Olive, R. J. Loughran & J. A. Kesby) (Proc. Canberra Symp., December 1994), 343-350. IAHS Publ. no. 224.

Lawler, D. M., Dolan, M., Tómasson, H. & Zophoniasson, S. (1992) Temporal variability of suspended sediment flux from a subarctic glacial river, Southern Iceland. In: *Erosion and Sediment Transport Monitoring Programmes in River Basins* (ed. by J. Bogen, D. E. Walling & T. Day) (Proc. Oslo Symp., August 1992), IAHS Publ. no. 210.

Maizels, J. K. (1983) Proglacial channel systems: change and thresholds for change over long, intermediate and short timescales. *Special Publication of the International Association of Sedimentologists no. 6*, 251-266.

Pålsson, S. & Vigfusson, G. H. (1991) *Nidurstödur Svifaursmaelinga 1963-1990.* Orkustofniu Report OS-91017/VOD031B.

Raymond, C. F., Benedict, R. J., Harrison, W. D., Echelmeyer, K. A. & Sturn, M. (1995) Hydrological discharges and motion of Fels and Black Rapids Glaciers, Alaska, USA: implications for the structure of their drainage systems. *J. Glaciol.* **41**, 290-304.

Rist, S. (1990) Vatns er pöf. *Bókautgáfa Menningarsjóds.* Orkustofnin, Reykjavik.

Repp, K. (1988) The hydrology of Bayelva, Spitsbergen. *Nordic Hydrol.* **19**, 259-268.

Tómasson, H. (1991) Glaciofluvial sediment transport and erosion. In: *Arctic Hydrology: Present and Future Tasks* (ed. by Y. Gjessing, J. O. Hagen, K. A. Hassel, K. Sand & B. Wold), 27-36. Norwegian National Commission for Hydrology, Oslo, Report 23.

Walling, D. E. and Kleo, A. (1979) Sediment yields of rivers in areas of low precipitation: a global view. In: *The Hydrology of Areas of Low Precipitation* (Proc. Canberra Symp., December 1979), 479-493. IAHS Publ. no. 128.