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Short-term spatial and temporal patterns of suspended sediment transfer in proglacial channels, Small River Glacier, Canada

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Abstract:

Alpine glacial basins are a significant source and storage area for sediment exposed by glacial retreat. Recent research has indicated that short-term storage and release of sediment in proglacial channels may control the pattern of suspended sediment transfer from these basins. Custom-built continuously recording turbidimeters installed on a network of nine gauging sites were used to characterize spatial and temporal variability in suspended sediment transfer patterns for the entire proglacial area at Small River Glacier, British Columbia, Canada. Discharge and suspended sediment concentration were measured at 5 min intervals over the ablation season of 2000. Differences in suspended sediment transfer patterns were then extracted using multivariate statistics (principal component and cluster analysis). Results showed that each gauging station was dominated *c*. 80% of days by diurnal sediment transfer patterns and 'low' suspended sediment concentrations. 'Irregular' transfer patterns were generally associated with 'high' sediment concentrations during snowmelt and rainfall events, resulting in the transfer of up to 70% of the total seasonal suspended sediment load at some gauging stations. Suspended sediment enrichment of up to 600% from channel storage release and extrachannel inputs occurred between the glacial front and distal proglacial boundary. However, these patterns differed significantly between gauging stations as determined by the location of the gauging station within the catchment and meteorological conditions. Overall, the proglacial area was the source for up to 80% of the total suspended sediment yield transferred from the Small River Glacier basin. These results confirmed that sediment stored and released in the proglacial area, in particular from proglacial channels, was controlling suspended sediment transfer patterns. To characterize this control accurately requires multiple gauging stations with high frequency monitoring of suspended sediment concentration. Accurate characterization of this proglacial control on suspended sediment transfer may therefore aid interpretation of suspended sediment yield patterns from glacierized basins. Copyright © 2004 John Wiley & Sons, Ltd.

KEY WORDS proglacial channels; suspended sediment; suspended sediment yield; Small River Glacier

INTRODUCTION

The proglacial zone in alpine glacial basins is a significant source and storage area for sediment exposed by glacial recession. Transfer of this sediment to the wider environment is usually dominated by transport in suspension by proglacial streams (Gurnell, 1987). Patterns of suspended sediment transport have therefore been used to investigate the rates and timing of overall sediment transfer and the development of subglacial erosion systems (e.g. Hammer and Smith, 1983; Willis *et al*., 1996). These transfer patterns have also been used as an indication of the efficacy of glacial erosion and therefore as a measure of glacial denudation (e.g. Hallet *et al*., 1996). However, recent research has indicated that short-term storage and release of sediment in proglacial channels may control these patterns (Warburton, 1990). As a result, the role of proglacial channels

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in modifying suspended sediment transfer needs to be established before overall sediment yield patterns from glacierized basins can be interpreted (Harbor and Warburton 1993; Warburton, 1999).

Short-term storage and release of suspended sediment in proglacial channels varies spatially and temporally (Gurnell and Warburton, 1990). This variability is due largely to fluctuations in channel sediment sources and sinks, seasonal influences on transfer processes and diurnal variations in meltwater discharge. However, spatial measurements of these sediment transfer patterns are commonly based on a single gauging site at an arbitrary distance from the glacial front (e.g. Collins, 1998). Transfer patterns observed at these sites are likely to be a function of their position along the channel because distance from the glacier front determines the potential for sediment storage and remobilization and therefore modification of transfer patterns (Harbor and Warburton, 1993). Limited sampling sites may therefore provide only coarse approximations of proglacial suspended sediment transfer patterns. Temporal precision will be determined by the sampling frequency as continuous monitoring of proglacial suspended sediment has shown high variability over time (Gurnell and Warburton, 1990; Clifford *et al.*, 1995). Because of this, discrete sampling (e.g. hourly) is unlikely to characterize temporal variations in suspended sediment transfer patterns and may result in significant underestimation of suspended sediment loads.

Accurate characterization of the proglacial channel control on suspended sediment patterns is therefore best achieved by spatially distributed networks of gauging stations that provide high-frequency temporal records of suspended sediment. The objective in this paper was to characterize this proglacial channel control over a 9 week ablation season in the summer of 2000 using continuously recording turbidimeters on a network of gauging stations that sampled the entire proglacial area of a Canadian Rockies field site. Spatial characterization of the resulting suspended sediment transfer patterns was used to interpret variability for the whole proglacial area. To do this, multivariate statistical techniques were used to identify and characterize differences in suspended sediment transfer patterns at each gauging station. Comparison of suspended sediment yields with contemporaneous meteorological data allowed identification of any seasonal influence on transfer patterns over the course of the ablation season. These patterns were then used to assess the overall implications of proglacial channel contribution to suspended sediment yield patterns from glacierized basins.

FIELD SITE

The Small River Glacier field site is a small cirque basin located in the western ranges of the Canadian Rocky Mountains (53°11′N, 119°30′W) (Figure 1). Massive limestone with interstratal dolomite and shale units of the Mural and Mahto Formations dominate the underlying geology (Huntley, 1990). Montane forest occupies the lower basin below an altitude of approximately 1750 m. The upper basin occupies 6·86 km^2 with elevations ranging from 1750 to 2600 m. Approximately 50% of the upper basin is glacierized and is divisible into three main glacial zones: North Cirque, North Lobe and Small River Glacier (Figures 1 and 2). North Cirque is an isolated, south-facing cirque glacier that formerly flowed into North Lobe and Small River Glacier. North Lobe is presently a stagnant extension of Small River Glacier. Small River Glacier constitutes the main glacier and currently occupies a deeply entrenched valley.

Glacial retreat has exposed a distinctive proglacial area (Figures 1 and 2). This area extends from the current ice front to the terminal moraines, an area of *c*. 2·0 km^2. Large deposits of till, prominent lateral and terminal moraines and bare bedrock surfaces characterize this area. Available lichenometric and dendrochronological dates on the main terminal moraine sequence for Small River Glacier indicate that the innermost well-developed moraines date at *c*. 1910 (Luckman, 1995).

Three main streams drain the proglacial area (Figure 1). The first of these, Central Proglacial Stream, drains the lower tongue of Small River Glacier and has a catchment area of 0·84 km^2, of which 60% is ice-free. The upper reaches of this stream divide into southern and northern tributaries that join approximately 10 m downstream of the glacial snout to form the main stream. The southern tributary exits directly from underneath the glacier. Suspended sediment transferred from this tributary therefore represents ‘direct’ subglacial sediment

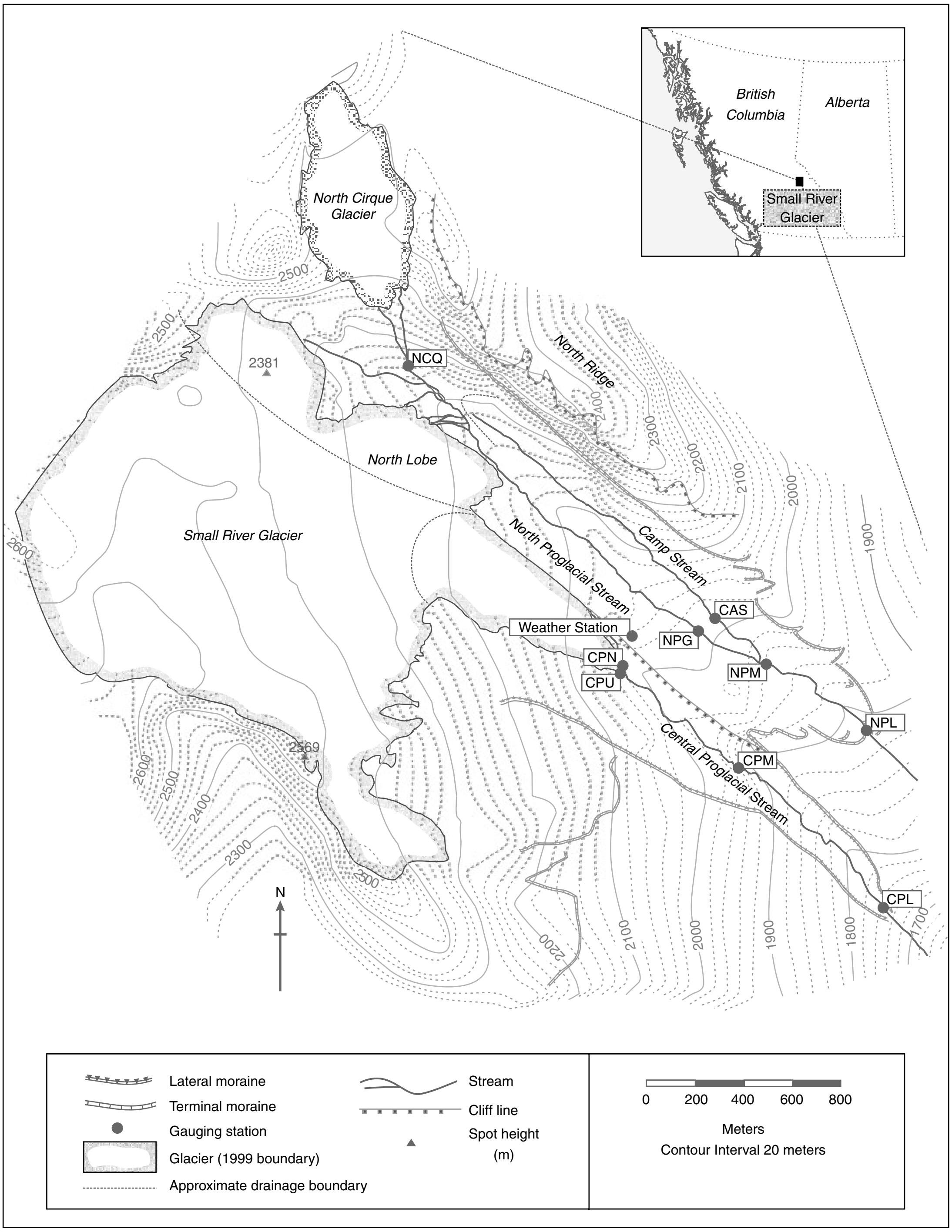

Figure 1. Location map of Small River Glacier. Gauging station locations referred to in the text are as follows: NPL, North Proglacial Lower; NPM, North Proglacial Middle; NPG, North Proglacial; CAS, Camp Stream; NCQ, North Cirque; CPL, Central Proglacial Lower; CPM, Central Proglacial Middle; CPU, Central Proglacial Upper; CPN, Central Proglacial North

Figure 2. Westward looking photograph of the upper Small River Glacier proglacial area. Small River Glacier is to the left and North Cirque in the upper-right corner. North Proglacial and Camp Streams are marked. Central Proglacial Stream is out of picture to the left. Note the well defined lateral moraines to the upper right of Camp Stream and the variability in surficial sediment

input (CPU on Figure 1). The northern tributary debouches from the debris-free glacier surface on to an extensive area of recently exposed till at the ice margin, approximately 400 m from its confluence with the southern tributary. Sediment transferred from this tributary to the main Central Proglacial Stream therefore represents suspended sediment input from the proglacial area (CPN on Figure 1).

The second stream, North Proglacial Stream, drains North Cirque and is ice-marginal to North Lobe. This stream has a catchment area of 2·60 km^2, of which 70% is ice-free. A gauging station was not able to be established at the snout of North Cirque owing to multiple subglacial streams and unstable cross-sections. A gauging station was therefore installed 400 m downstream (NCQ on Figure 1). Immediately upstream of this gauging station is a large area of unconsolidated till. Suspended sediment transferred at this site therefore reflects both 'direct' glacial input of sediment and sediment input from the proglacial area. The final stream, Camp Stream, is spring-fed and as such functions as a 'non-glacial' stream with a catchment area of 0·47 km^2.

METHODS

Gauging station network

Nine gauging stations were established within the Small River proglacial area (Figure 1). The location of each station was designed to ensure as wide a spatial representation as possible. However, the availability of a single channel with a stable cross-section ultimately determined each location.

Discharge, turbidity and meteorological data

Discharge and suspended sediment were monitored at each site from 7 July (Julian Day 188) to 26 August 2000 (Julian Day 238) (approximately 80% of the ablation season). Rating curves were used to convert stage measurements into discharge. Druck 1·5 p.s.i. pressure transducers were used to measure stage with Campbell Scientific UDG-01 and SR50 ultrasonic depth gauges used in the more turbulent reaches. Approximately 10 NaCl dilution gaugings per site under different flows were used to establish stage–discharge relationships. Fitted power rating curves gave r^2 values of 0·78 to 0·99.

High-frequency records of suspended sediment concentration using turbidimeters provide a solution to the temporal problem of suspended sediment sampling (Gippel, 1989). However, spatially distributed sampling is constrained by the cost of establishing networks of turbidimeters. An inexpensive turbidimeter was therefore custom-designed (Orwin, 2002). The sensor array was based around a matching infrared LED emitter and photodiode detector with a 180° backscatter geometry. Laboratory testing using sediment collected from Small River showed that the turbidimeter was most sensitive to coarse clay (d_{50} of *c*. 2·19 μm) and fine silt (d_{50} of *c*. 120 μm) fractions. These fractions generally dominate the particle sizes transported in proglacial streams (Gurnell, 1987). Further details on the construction of the turbidimeter are presented elsewhere (Orwin, 2002).

Each gauging station's turbidimeter was field calibrated with between 50 and 100 suspended sediment samples collected with ISCO 6400 automatic water samplers. Samples were vacuum-filtered using pre-dried and pre-weighed Whatman 40 Ashless (8 μm) filter papers, dried in desiccators for 24 h, reweighed and suspended sediment concentration was calculated. The accuracy of determining suspended sediment concentration using this method has been estimated at between ±2 and 4% when the filters were oven dried at 105 °C (Gilvear and Petts, 1985; Gurnell *et al*., 1992a). As this study did not use ovens in the field, errors were likely to be higher than this. Although the retention size of the Whatman filters allows for fast filtration and therefore rapid field processing of large numbers of samples, the relatively coarse retention size may result in sediment losses of up to *c*. 4% for concentrations below 1000 mg/L (Gurnell *et al*., 1992a). This may further increase error in determining suspended sediment concentrations. Following processing, the water sampler concentrations from each site were compared with the concurrent reading of the associated turbidimeter and a calibration equation generated. The resulting calibrations were then used to convert the turbidity signals to suspended sediment concentration estimates.

The turbidimeters showed linear responses up to 2000 mg/L and non-linear responses for ranges up to 10 000 mg/L, with explained variances between 75 and 83%. This variability was most likely the result of measurement errors but also the influence of changing particle size under different flow conditions affecting the turbidimeter response. For example, an increase in sand-size particles under higher discharges would result in a reduced signal from the turbidimeter relative to an apparent increase in suspended sediment concentration owing to the increased mass. This reduced signal combined with errors in discharge measurement would result in potential underestimation of the total suspended sediment yield during high discharge events. However, these problems are outweighed by the benefit of high-frequency data (Gurnell and Warburton, 1990).

A centrally located automatic weather station at an altitude of 2089 m was used to collect meteorological data (Figure 1). Rainfall and temperature were measured using a Campbell Scientific Model TB4 0·1 mm precision tipping bucket rain gauge and a shielded Campbell Scientific 107B temperature sensor. Humidity and global solar radiation were recorded using a Campbell Scientific 207 RH probe and a LICOR LI-200SA pyranometer. Two rain gauges were also installed at 2125 m (North Lobe, Figure 1), and at 2015 m (CAS, Figure 1) to assess any variation in rainfall. No significant differences were recorded.

All instruments were connected to either a Campbell Scientific CR-10 or 21X datalogger and programmed to make readings every 10 s, with final values averaged and stored every 5 min. Power supply for the dataloggers was provided by solar panel charged NiCd batteries.

ANALYSIS

Objective and approach

Identifying and characterizing the extent of proglacial channel control on suspended sediment transfer patterns required an appropriate analytical procedure to extract these patterns from the large amount of data generated from the gauging site network, without degrading the temporal precision. Two multivariate statistical techniques, principal component analysis (PCA) and cluster analysis (CA) were therefore used.

Principal component and cluster analysis are used to reduce large data sets to a more manageable size, maintaining as much of the underlying structure as possible (Rogerson, 2001). Principle component analysis reduces data sets to a smaller number of underlying components. These components represent a large proportion of the data set variability and, for this paper, allowed physically based interpretations of the component loadings and scores (Jolliffe, 1990, 1993; Rogerson, 2001). In contrast, CA searches rows in a data table to reduce *n* original observations into 'like-groups' (Rogerson, 2001). A hierarchical agglomeration method (Ward's) is commonly used as this results in the smallest increase in the within-sum of squares, maintaining the within-group variability to a minimum. An agglomeration dendrogram can then be plotted and breaks visually identified to determine the number of clusters. Descriptive titles can then be assigned using the raw data represented by each cluster. Combining the PCA and CA results allows identification of patterns and interpretation of the controls on those patterns (Hannah *et al.*, 2000).

Procedure

The proglacial hydrograph classification developed by Hannah *et al.* (2000) was the basis for the analytical procedure used in this paper. Their approach combined PCA and CA to classify discharge time-series on the basis of hydrograph 'shape' and 'magnitude'. The resulting classification was successfully used to isolate and identify seasonal-scale evolution and downstream changes in proglacial hydrographs. This classification can be applied to any time-series with an underlying cyclic structure and where characterization of 'shape' and 'magnitude' may provide useful physical interpretations (e.g. Harris *et al.*, 2000). As proglacial suspended sediment concentration has a cyclic structure related to changes in discharge and sediment sources (Gurnell, 1987), differences in sedigraph 'shape' and 'magnitude' patterns could be used to infer controls on these patterns. This method was therefore considered suitable for identifying and characterizing the proglacial control on sediment transfer patterns at Small River.

Four separate classification procedures were used to extract these sediment transfer patterns (Figure 3). The first classification identified differences in discharge-generating processes using PCA. The next two classifications characterized the suspended sediment data into diurnal suspended sediment 'shape' and 'magnitude' classes for individual days at each gauging station, using PCA and CA respectively. These classes were then plotted with discharge and meteorological data to visually identify differences in transfer patterns between the gauging stations. The fourth classification divided the ablation season into distinct meteorological periods, using CA. These periods were used to examine any seasonal influence on suspended sediment transfer patterns. All data sets were partitioned using hydrological days (6 am to 6 am the following day) to minimize the influence of the previous day's peak in suspended sediment and discharge. A computer-based statistical package, SPSS (Version 8·0), was used to run the PCA and CA analyses. These classifications were applied separately to each gauging station's suspended sediment concentration record.

Classification of discharge generating processes—method

The input matrix for PCA consisted of *N* columns of daily averages of discharge for each station, average, minimum and maximum air temperature, total daily rainfall and total daily solar radiation by *n* rows of days. Principle component analysis was run using a VARIMAX orthogonal rotation to maximize loadings on the variables with standard retention criteria.

Classification of daily suspended sediment 'shape'—method

The number of underlying components that explained the sediment transfer patterns was identified using PCA. The input matrix consisted of *N* columns of days by *n* rows of 5-min suspended sediment concentration data. Use of high-frequency data is important as the matrix for PCA must have more rows than columns to prevent algebraic problems (Jolliffe, 1986; Hannah *et al.*, 2000). The analysis was performed using a VARIMAX

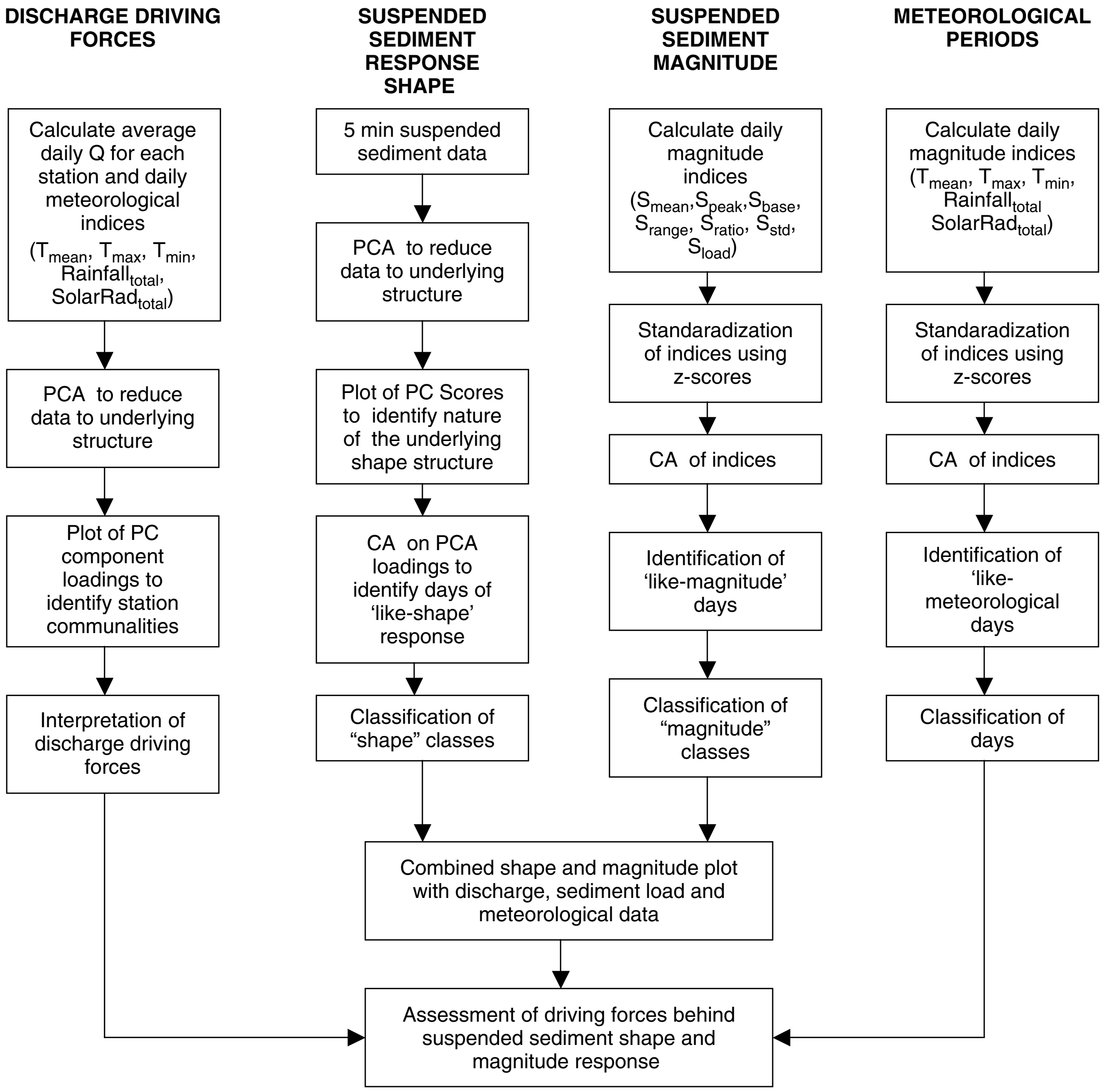

Figure 3. Flow chart detailing the classification procedures used to extract the suspended sediment transfer patterns: Q, discharge; T, temperature (°C); S, suspended sediment concentration (mg/L); Rainfall (mm); SolarRad(iation) (MW/day)

orthogonal rotation to maximize loadings on the variables with standard retention criteria. Components with an Eigenvalue >1 were retained. Principal component scores were exported as variables and plotted against time to reveal the underlying ‘shape’ of the retained components at each gauging station.

Individual days with comparable suspended sediment response ‘shape’ were identified using CA. Clustering was run on the exported component loadings for each of the gauging station’s retained components. The observations were standardized to z-scores (mean = 0; standard deviation = 1) to remove major variations in the magnitude of observations. The CA was run using Ward’s method as this showed more physically interpretable clusters. An agglomeration dendrogram was then plotted and the number of clusters determined by visual examination. Appropriate ‘shape’ titles were then assigned to each cluster. The raw data identified in these clusters were then visually checked for consistency in ‘shape’ structure.

Classification of daily suspended sediment 'magnitude'—method

This classification was based on CA of daily bulk sediment indices, as suggested for discharge by Hannah *et al*. (2000). These included: mean daily concentration, daily concentration range, daily concentration standard deviation, daily minimum and peak concentration and total load. Rainfall days were included in the analysis. All daily indices were calculated in milligrams per litre except for suspended sediment load, which was expressed as kilograms per hydrological day.

The observations were again standardized to z-scores. Cluster analysis was run using Ward's method and an agglomeration dendrogram of 'like-magnitude' days plotted. Breaks in the dendrogram were identified and the raw magnitude data contained within each cluster examined to assign a 'magnitude' class for each day.

Classification of daily meteorological data—method

Clustering was applied to the seasonal record of daily indices of average, maximum and minimum temperature; average relative humidity, total daily global solar radiation and total daily rainfall. The observations for each of the indices were also standardized to z-scores. Cluster analysis was run using Ward's method and an agglomeration dendrogram of 'like-meteorological' days plotted. Breaks in the dendrogram were identified and the data contained within each cluster examined to assign a 'meteorological period' classification.

RESULTS AND DISCUSSION

Data record

Sustained records of discharge and suspended sediment concentration were maintained for seven gauging stations (Table I and Figure 4). Data for incomplete hydrological days were removed from the records before analysis. Data records from Central Proglacial Middle and Central Proglacial North gauging stations were not used owing to discontinuous suspended sediment measurements. This discontinuity was caused by continual blockage of the turbidimeter intakes under high sediment load (concentrations of up to 12 000 mg/L were commonly observed). Field observations showed that the dominant sediment source for this high suspended sediment load was a recently exposed, unconsolidated till surface dissected by Central Proglacial Stream's northern tributary. This indicated that a significant proportion of the suspended sediment transferred in the upstream reaches of Central Proglacial Stream was sourced from the proglacial area rather than from 'direct' glacial sediment input.

Table I. Length of each gauging station's data record. Letter codes refer to individual gauging stations (see Figure 1). Central Proglacial Middle and North gauging stations were removed from the analysis

Data Record	Station Identity						
	NPL	NPM	NPG	CAS	NCQ	CPL	CPU
Number of days in individual record	41	41	45	45	24	37	40
Number of missing days	4	7	5	5	2	9	0
Percentage missing of individual record	10	17	11	11	8	24	0
Number of days in season	49	49	49	49	49	49	49
Percentage missing of season total	16	16	8	8	51	24	18

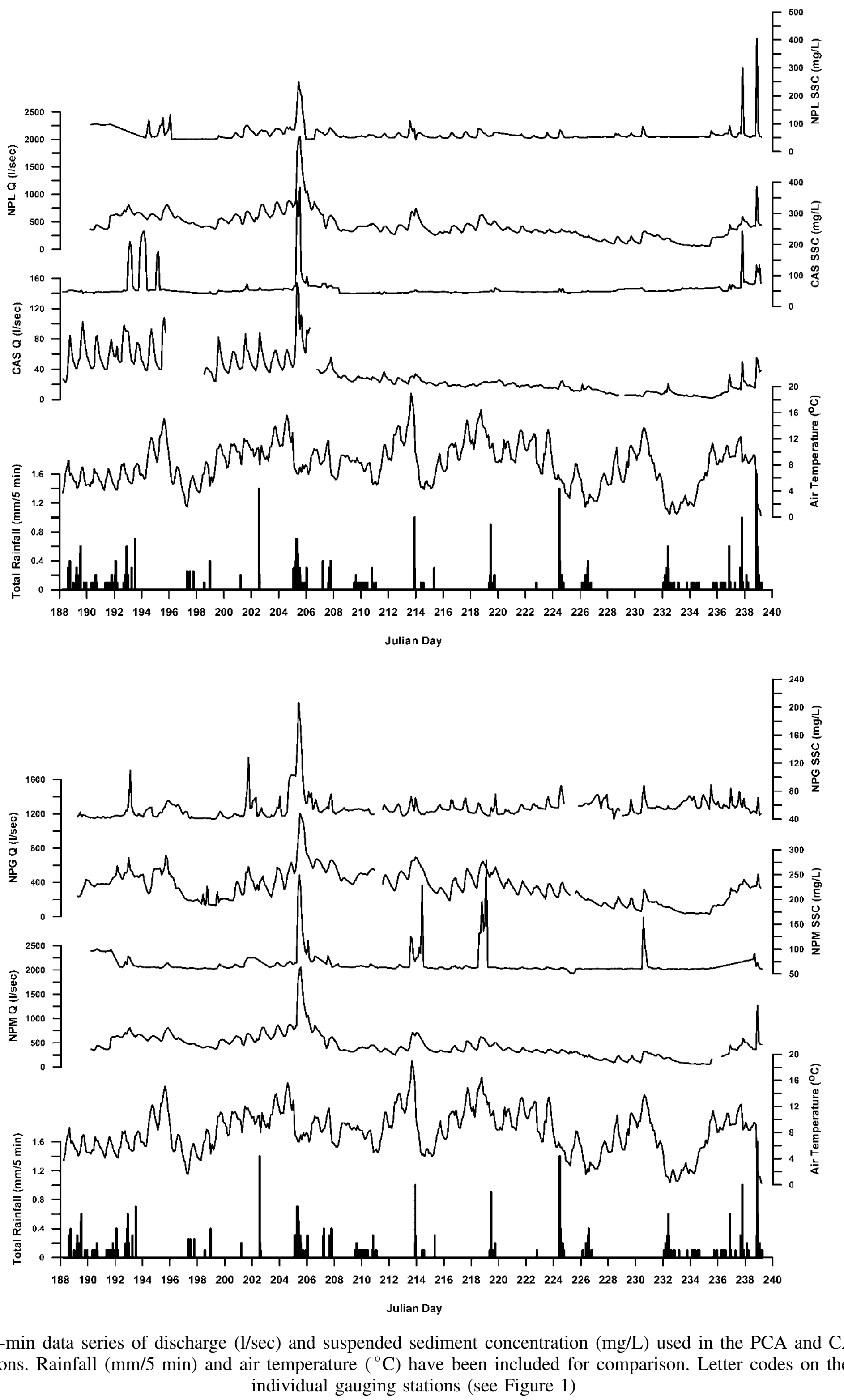

Figure 4. Raw 5-min data series of discharge (l/sec) and suspended sediment concentration (mg/L) used in the PCA and CA analyses for all gauging stations. Rainfall (mm/5 min) and air temperature (°C) have been included for comparison. Letter codes on the axes refer to individual gauging stations (see Figure 1)

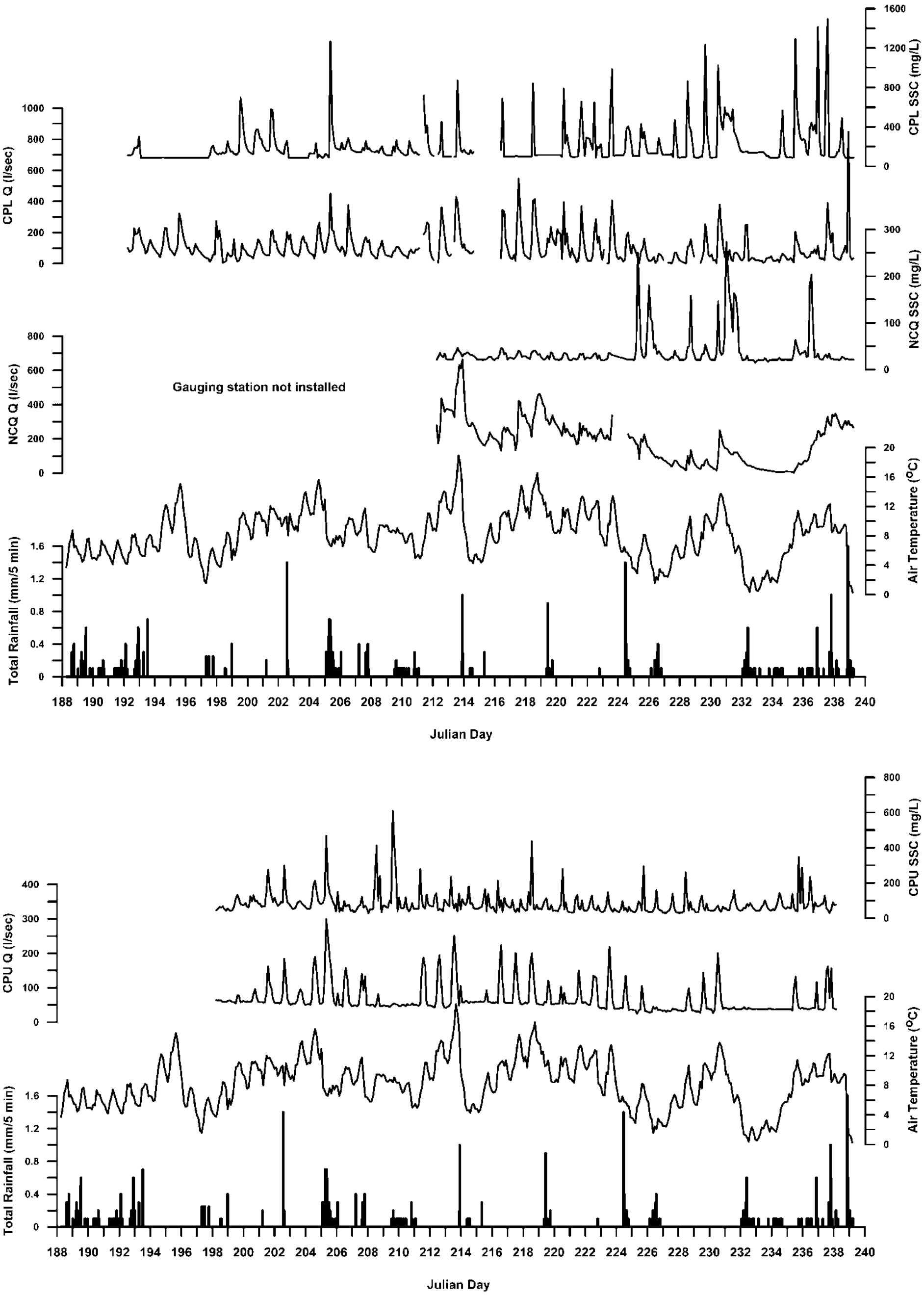

Figure 4. (*Continued*)

Discharge generating processes

The analysis retained two components from the combined daily discharge and meteorological records (Figure 5). These explained 55% and 22%, respectively, of the total variability. The first component was interpreted as showing the dominance of ablation on discharge patterns (for which temperature variables serve as a surrogate), and the second, rainfall events. However, the dominance of ablation or rainfall differed between gauging stations. For example, the Central Proglacial Stream gauging stations and the gauging station at North Cirque loaded positively on ablation but slightly negatively on rainfall. This loading was interpreted as indicating a stronger ablation influence than rainfall on discharge patterns for these gauging stations. Snowfall at higher elevations may have also resulted in a reduced rainfall response at the North Cirque gauging station, which is significantly higher in elevation (2232 m). In contrast, the lower North Proglacial gauging stations and the gauging station at Camp Stream loaded positively on both ablation and rainfall. The inclusion of a rainfall response in these discharge records was probably due to a larger deglacierized contributing area and therefore to greater runoff during rainfall events than on Central Proglacial Stream. These results indicated that the three proglacial streams could be divided into two hydrologically distinct groupings, one dominated by ablation and one influenced more by rainfall than ablation. It is these distinctions in discharge forcing that should, to a large extent, control the temporal and spatial pattern of proglacial suspended sediment transfer (Clark, 1987; Hodson and Ferguson, 1999).

Suspended sediment 'shape'

Three components were retained for the suspended sediment time-series for each gauging station. The first component explained an average of 37% of the variance, the second 20% and the third 10% (Figure 6). The structure of the first two components showed that a 'diurnal' suspended sediment response pattern dominated transfer patterns at all gauging stations over the course of the ablation season (Figure 6). The structure of the third component showed a more 'irregular' response pattern. The increasing peakedness in the suspended sediment response shape between Camp Stream, North Proglacial Stream and Central Proglacial Stream was interpreted as the increasing dominance of ablation-driven discharge, commensurate with the increase in glacial ice-cover between the three subcatchments. The score plots also showed differences in the 'time to peak' of suspended sediment concentration at the gauging stations on Central Proglacial Stream and at North Cirque. This was interpreted as indicating increasing rationalization of the glacier drainage system during the ablation season, resulting in earlier peak discharges and therefore peak suspended sediment concentrations (e.g. Gurnell *et al.*, 1992b; Hodgkins, 2001).

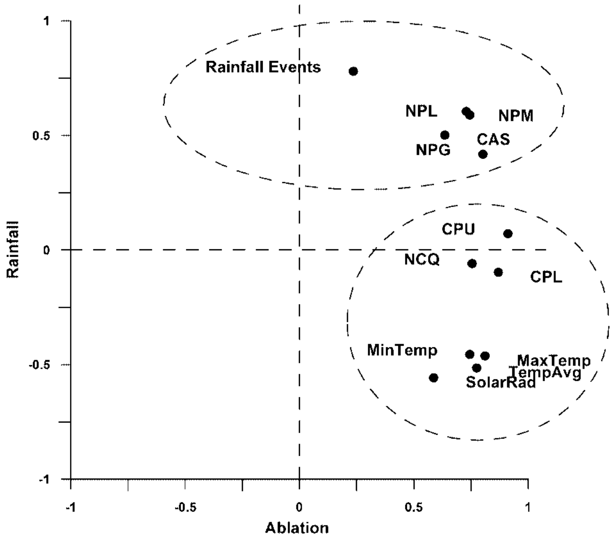

Figure 5. Principal component loadings for meteorological variables and all stations for the ablation season of 2000. Station groupings indicate the relative dominance of ablation and/or precipitation on discharge generation for each gauging station. The 'Ablation' and 'Rainfall' PC's explain 55% and 22%, respectively, of the total variance in the PCA. Letter codes refer to individual gauging stations (see Figure 1)

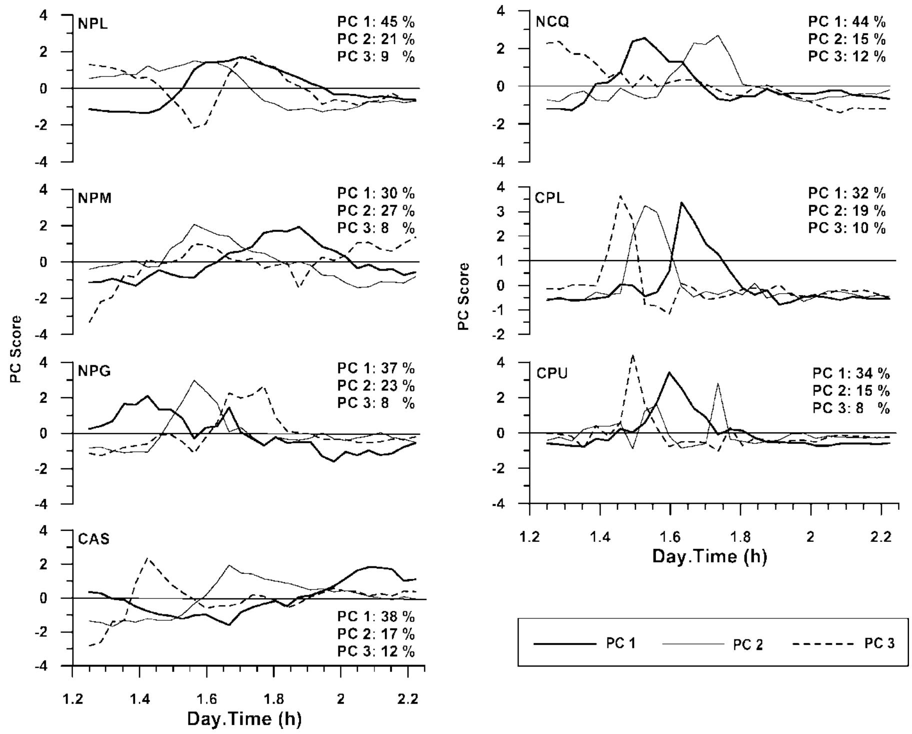

Figure 6. Principal component loadings and scores for individual gauging stations derived from 5 min suspended sediment concentration readings for the ablation season of 2000. The line graphs show the underlying diurnal structure for each of the three retained principal components. Note the increasing peakedness on NCQ, CPL and CPU, interpreted as indicating the increasing dominance of ablation driven discharge on suspended sediment transfer patterns

Cluster analysis on the component loadings for each gauging station confirmed the 'shape' classes. On average, *c*. 75% of all days had a diurnal response 'shape'. The remaining days had an irregular response 'shape'. Plots of the sedigraph for each day within these clusters confirmed the dominance of a diurnal response pattern at each gauging station.

Suspended sediment 'magnitude'

The 'magnitude' of suspended sediment response was classified into 'high' and 'low' classes at each gauging station. Each station's record was dominated by a 'low' magnitude class that represented, on average, 80% of the days recorded (Table II). The remaining days were classified as 'high' magnitude. However, there were significant differences in the actual suspended sediment concentrations within these magnitude classes (Table II). For example, the mean suspended sediment concentration for the 'low' magnitude class for Central Proglacial Upper and Central Proglacial Lower gauging stations were 156 and 70 mg/L respectively, compared with 54, 65 and 55 mg/L for North Proglacial Lower, North Proglacial Middle and North Proglacial gauging stations. Mean concentration at the Camp Stream gauging station was similar to North Proglacial Stream at 50 mg/L. These differences were consistent for both magnitude classes and were interpreted as indicating greater sediment availability in the Central Proglacial Stream channel, particularly in the upper reaches, than in the North Proglacial Stream and Camp Stream channels.

Composite daily suspended sediment 'shape' and 'magnitude' response

The 'shape' and 'magnitude' classes were cross-tabulated and plotted with discharge and meteorological data. These graphs were used to determine whether differences in catchment and meteorological conditions

Table II. Average suspended sediment concentrations and loads for 'high' and 'low' magnitude classes for each gauging station. Standard deviations are shown in parentheses

Station	Magnitude class	S_{mean} (mg/L)	Average S_{peak} (mg/L)	Average S_{base} (mg/L)	Average S_{range} (mg/L)	Average S_{std} (mg/L)	Average S_{load} (kg per day)	Number of days
NPL	Low	54 (5)	66 (15)	49 (3)	17	4 (4)	1495 (677)	28
	High	72 (11)	139 (70)	50 (6)	89	20 (14)	4791 (2613)	13
NPM	Low	65 (7)	78 (27)	61 (6)	17	3 (3)	2163 (1130)	37
	High	109 (28)	322 (34)	64 (5)	257	54 (16)	8374 (7818)	4
NPG	Low	55 (7)	66 (12)	47 (5)	18	5 (3)	1506 (751)	38
	High	74 (21)	203 (87)	49 (8)	154	30 (14)	3565 (3048)	7
CAS	Low	50 (6)	59 (16)	47 (5)	120	3 (2)	120 (80)	39
	High	105 (30)	317 (135)	56 (8)	262	68 (28)	605 (451)	6
NCQ	Low	28 (6)	52 (31)	19 (3)	33	8 (7)	480 (366)	20
	High	88 (16)	244 (33)	21 (0)	223	71 (13)	1035 (243)	4
CPL	Low	156 (56)	398 (261)	101 (20)	296	67 (58)	1446 (785)	29
	High	316 (92)	1586 (308)	88 (15)	1498	289 (55)	4449 (1645)	8
CPU	Low	70 (11)	227 (80)	36 (8)	191	36 (13)	382 (144)	27
	High	110 (26)	460 (80)	38 (11)	422	89 (30)	827 (481)	13

generated distinctive responses at each gauging station. Differences in response were identified visually by comparing the daily relationship between 'shape' and 'magnitude' classes, discharge and meteorological data (e.g. Figure 7).

The composite graphs showed distinct response differences between gauging stations. For example, 'low' magnitude events at the Central Proglacial Lower gauging station were generally associated with cool temperatures ($<10\,^{\circ}$C) and a diurnal response. 'High' magnitude events and an irregular response shape were associated with high temperatures ($>10\,^{\circ}$C) but also some rainfall events. This was interpreted as showing that sediment transfer patterns were responding to sediment mobilized from bank collapse and/or sediment mobilized from the channel during periods of high, ablation driven discharge (Figure 8) as well as rainfall events of enough intensity to mobilize extra- and inchannel sediment sources. In contrast, 'high' magnitude events at the ice-proximal Central Proglacial Upper gauging station were exclusively associated with high temperatures and a diurnal 'shape'. This transfer pattern indicated that periods of high, ablation driven discharge were required to mobilize subglacial sediment and that rainfall events appeared to have no impact on suspended sediment transfer patterns.

Different response patterns were also evident between North Proglacial Stream and Camp Stream. 'Low' magnitude classes with a diurnal response shape dominated the patterns observed at North Proglacial, Middle and Lower gauging stations. 'High' magnitude events were closely associated with rainfall events and an irregular response shape, interpreted as being due to variability in the input of sediment mobilized on proglacial surfaces as well as from the channel during rainfall events. However, the transfer patterns at the upstream North Cirque gauging station were significantly different from those at the lower stations. Changes in temperature dominated the suspended sediment pattern at the North Cirque gauging station. 'High' magnitude events with an irregular response shape were associated with peaks in temperature and therefore periods of high, ablation driven discharge. However, the distance of the gauging station from the glacial snout made it difficult to determine if mobilization of suspended sediment was dominated by inchannel stores immediately upstream from the gauging station or by subglacial input. 'Low' magnitude events with a diurnal response shape corresponded to cooler temperatures. Rainfall did not appear to have a significant impact on suspended sediment response. 'Low' magnitude and a diurnal response shape dominated Camp Stream's sediment transfer pattern. 'High' magnitude days were exclusively associated with precipitation events. This was also interpreted as the input of sediment mobilized on proglacial surfaces, as observed in the field.

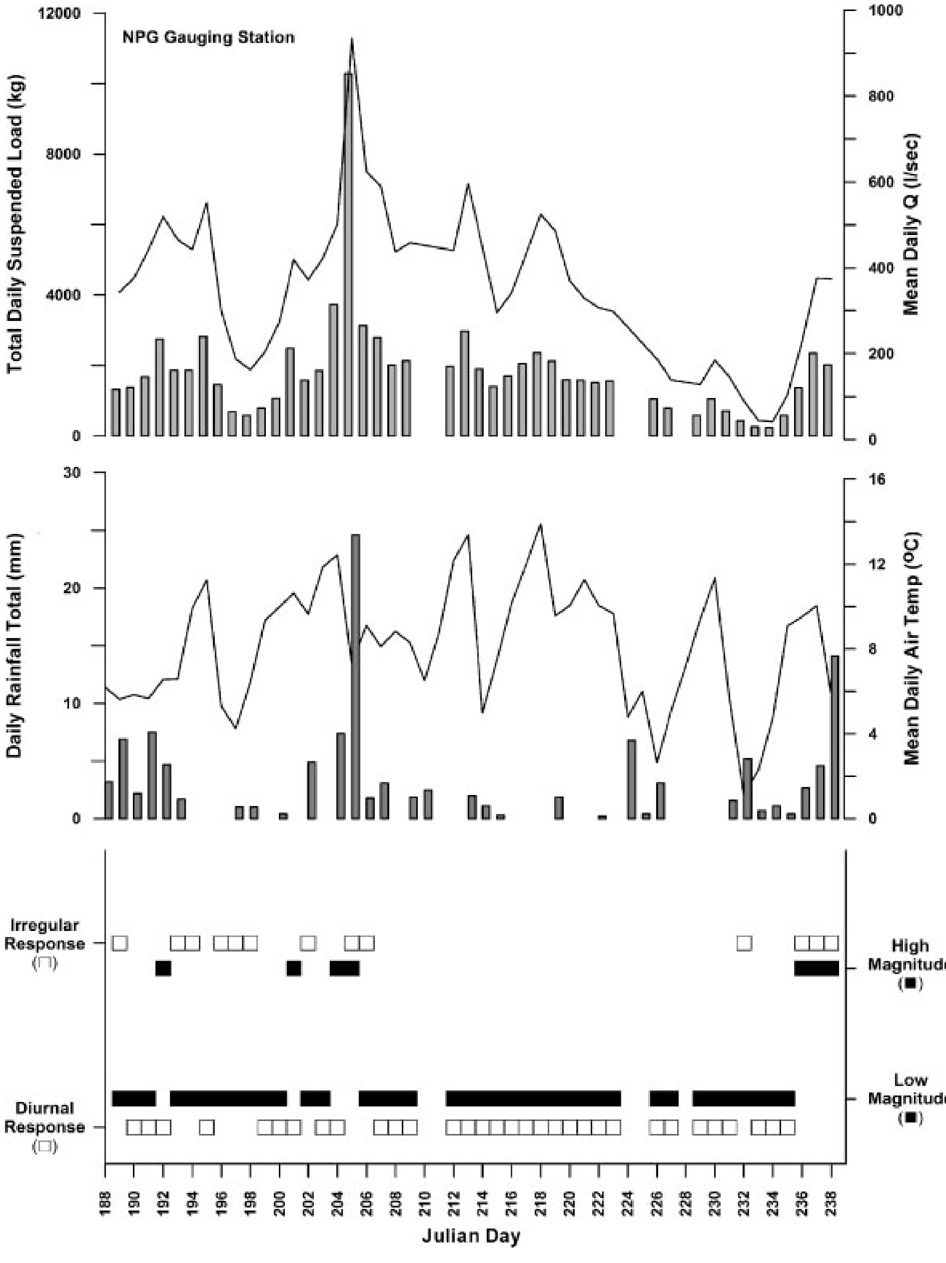

Figure 7. Example of a composite daily suspended sediment 'shape' and 'magnitude' response graph used to determine whether differences in catchment and meteorological conditions generated distinctive responses at each gauging station. The graph shown is for the North Proglacial gauging site where suspended sediment transfer patterns were dominated by a low 'magnitude' diurnal pattern. 'High' magnitude events were associated with rainfall events

Two-sample Chi^2 tests confirmed that most differences in suspended sediment transfer patterns between stations on the same channel and between each proglacial stream were statistically significant (Table III).

The multivariate statistical classification procedure used in this paper therefore clearly showed that differences in suspended sediment transfer patterns could be characterized using 'shape' and 'magnitude'

Figure 8. Examples of bank collapse (A) on North Proglacial Stream owing to bank undercutting, and channel sediment storage by infiltration into the channel bed (B) on Central Proglacial Stream. This stored sediment is subsequently released under high discharge conditions

data. This approach successfully identified that variations in suspended sediment transfer patterns were caused primarily by differences in the location of a gauging station within the catchment and meteorological conditions.

Table III. Chi[2] results matrix showing the probability of 'unlikeness' (at ∝ 0·05) in 'shape' and 'magnitude' responses between gauging stations. Frequency data on the number of days from each gauging site with: high-magnitude/diurnal shape; high-magnitude/irregular shape; low-magnitude/diurnal shape; low-magnitude/irregular shape were used for the test. Probabilities in italic indicate stations that were statistically different

	NPL	NPM	NPG	NCQ	CAS	CPL	CPU
NPL	—	0·291	*0·001*	*0·004*	0·159	0·262	*0·011*
NPM	—	—	0·106	*0·032*	*0·046*	0·268	*0·002*
NPG	—	—	—	*0·001*	0·624	*0·038*	*0·000*
NCQ	—	—	—	—	*0·002*	0·085	*0·001*
CAS	—	—	—	—	—	*0·001*	*0·009*
CPL	—	—	—	—	—	—	*0·000*
CPU	—	—	—	—	—	—	—

Variations in suspended sediment transfer patterns have also been linked to meteorological conditions by other authors. For example, Richards (1984) found that suspended sediment concentration in a Norwegian proglacial area increased sharply during storm events and concluded that this difference was largely the result of storm runoff accessing temporary extrachannel stores of suspended sediment. In contrast, other authors have associated periods of precipitation with decreases in diurnal suspended sediment concentrations as a result of lower temperatures reducing meltwater production and thus lowering discharge (e.g. Sawada and Johnson, 2000). Both of these responses were present in the patterns of suspended sediment transfer at Small River. These differences observed at Small River and elsewhere indicate the importance of meteorological forcing on suspended sediment transfer patterns (Gurnell, 1987). However, the spatial and temporal variation of suspended sediment response to meteorological conditions may change during the course of an ablation season. At Small River, the analysis was therefore expanded to identify any seasonal influence by examining suspended sediment loads during different meteorological periods throughout the ablation season.

Suspended sediment loads during different meteorological periods

Cluster analysis of the meteorological indices identified four distinct meteorological 'periods' for the ablation season. These were classified as: snowmelt, an intense rainfall event on Julian Day 205, a 'hot and dry' period and a 'cold and wet' period (Table IV).

Suspended sediment load patterns for individual gauging stations were significantly different for these periods (Figure 9). Sediment transfer in North Proglacial Stream and Camp Stream were highest during

Table IV. Summary statistics for the meteorological periods identified by the cluster analysis. Standard deviations are shown in parentheses

Meteorological period	Mean temperature (°C)	Temperature maximum (°C)	Temperature minimum (°C)	Mean relative humidity (%)	Mean windspeed (m/s)	Solar radiation per day (MW)	Mean rainfall per day (mm)	Days
Snowmelt	7·8 (2·4)	10·5 (2·7)	5·0 (2·0)	69 (17)	1·46 (0·4)	16 (4)	2	16
Julian Day 205 rainfall event	9·9 (3·6)	13·0 (5·4)	6·6 (0·7)	70·0 (27)	1·52 (0·6)	12	35 (total)	2
'Hot and dry'	10·0 (2·0)	13·0 (2·0)	6·6 (1·8)	56 (11)	1·77 (0·3)	18 (4)	0	19
'Cold and wet'	5·0 (2·0)	7·0 (2·0)	2·7 (2·6)	79 (10)	1·61 (0·3)	7 (1·0)	4	12

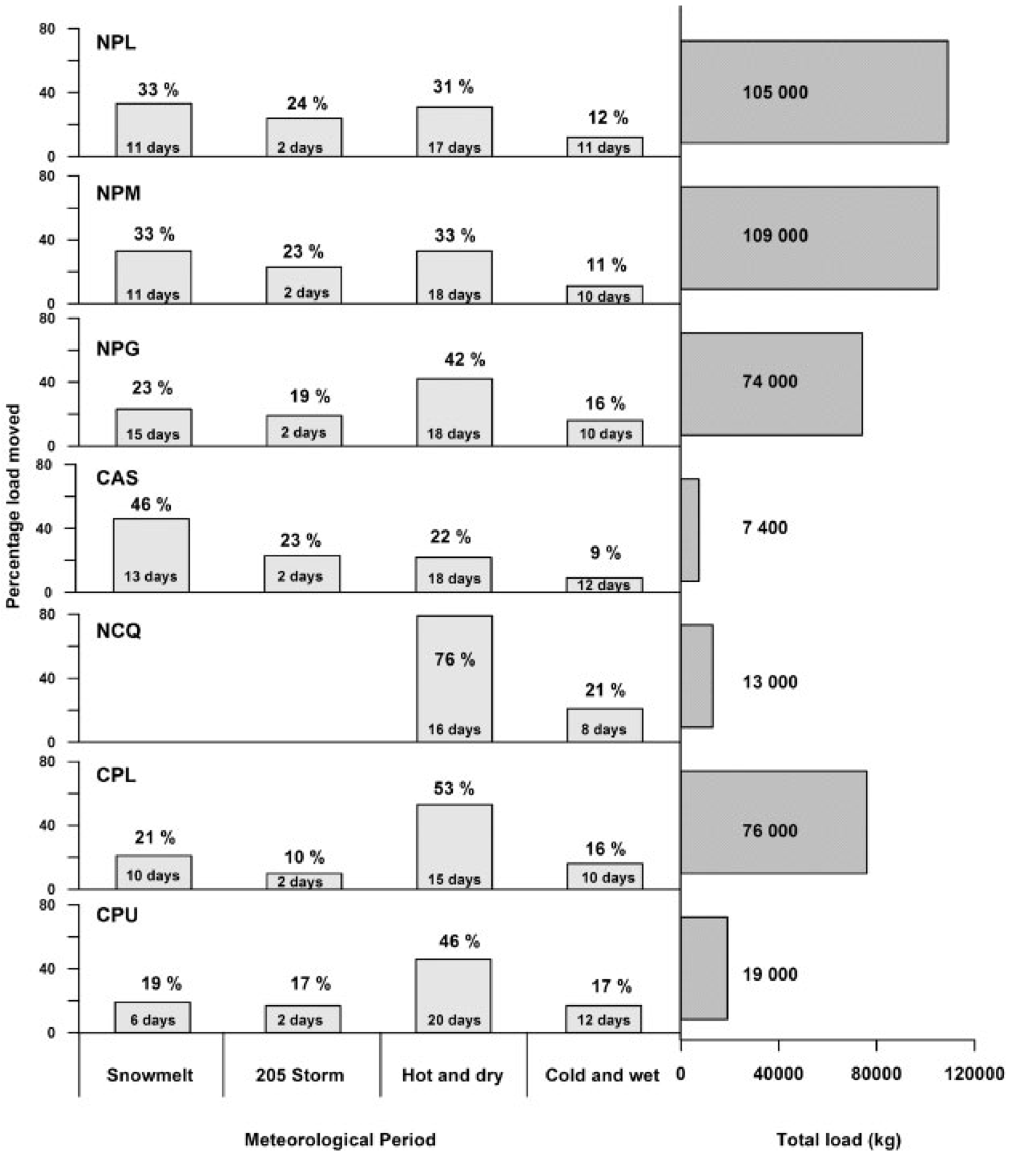

Figure 9. Suspended sediment load patterns for individual gauging stations during each meteorological period. Note that only loads from full hydrological days were used

snowmelt and the rainfall event on Julian Day 205. This was particularly evident for Camp Stream where almost 70% of the total observed load was transferred during these two periods. Approximately 60% of the total loads for the North Proglacial Lower and Middle gauging stations were also transferred during these two periods. This indicated that extrachannel suspended sediment mobilized by snowmelt or runoff was probably functioning as an important sediment source to channel sediment load in these catchments. However, less than 50% of the total load at the North Proglacial gauging station was transferred during these periods. A reduced load response was also apparent from both gauging stations in Central Proglacial Stream. This was most likely due to the continued presence of snowcover in the upper reaches of both North Proglacial and

Central Proglacial Stream retarding 'runoff' response, thus limiting suspended sediment response from both extra- and inchannel sediment sources.

Both gauging stations in Central Proglacial Stream and at North Cirque had *c*. 60% of their total load transferred during the 'warm and dry' period. This indicated that overall, the amount of sediment transferred at these stations was most likely being controlled by release of stored sediment in the proglacial channel during high, ablation driven discharge, particularly in Central Proglacial Stream. Yields during the 'cold and wet' period were significantly reduced for all stations, indicating that cool temperatures were reducing ablation-driven discharge and therefore sediment mobilization. The differences in response from individual stations during each of the meteorological periods indicated significant spatial variability in suspended sediment yield patterns.

This spatial variability in the proglacial channel control on patterns of suspended sediment transfer was highlighted by evaluating suspended sediment yield from representative common days for each meteorological period (Figure 10). For example, during the 'hot and dry' period on Central Proglacial Stream, initial input of 4400 kg of suspended sediment at the ice-proximal Central Proglacial Upper gauging site was enriched *c*. 600% to 30 000 kg at the distal Central Proglacial Lower site downstream. This enrichment presumably represented significant mobilization of sediment stored in-channel and/or episodic bank collapse owing to high discharge associated with increased ablation. This enrichment strongly indicates that sediment stored and released in the proglacial channel was the dominant sediment source rather than 'direct' glacial input of sediment. In contrast, during the 'Cold and Wet' period on North Proglacial Stream, an initial input of 1850 kg was enriched by only 220% to 5900 kg at the North Proglacial Lower gauging site downstream. Sediment load on Central Proglacial Stream was enriched even less (137%) for the same period. This was due to cooler temperatures reducing discharge and therefore mobilization of channel sediment. However, between North Proglacial Middle and North Proglacial Lower gauging stations, *c*. 2000 kg of sediment was lost to storage. This loss was most likely due to a decrease in the channel gradient, reducing flow competency and infiltration of fines into the gravel bed of the channel (e.g. Sambrook Smith, 2000) (Figure 8B). Similar patterns of enrichment were observed for the Julian Day 205 storm and during snowmelt.

Although the results presented here are from a single ablation season only, the combined evidence from all the comparisons is a strong indication that short-term storage and release of sediment in proglacial channels control suspended sediment transfer patterns rather than 'direct' glacial input of sediment. Differences in suspended sediment response 'shape' and 'magnitude' transfer patterns were determined by the location of the gauging station within the catchment and meteorological conditions. Spatial variability in these transfer patterns during different meteorological periods further validated the control of the proglacial channel on suspended sediment transfer patterns. The Small River results are supported by evidence from other studies that demonstrate the proglacial control on suspended sediment patterns (e.g. Gurnell, 1983; Ferguson, 1984; Richards, 1984; Gurnell and Warburton, 1990; Hodson *et al*., 1998). For example, 23% of the total suspended sediment yield from Bas d'Arolla Glacier over one ablation season was derived from the proglacial area (Warburton, 1990). Similarly, proglacial stream bank erosion accounted for up to a 35-fold increase in suspended sediment transferred from the Hilda Glacier in the Canadian Rockies, with the proglacial area supplying *c*. 50% of the total suspended sediment load (Hammer and Smith, 1983).

At Small River Glacier, the total load calculations presented in Figure 9 indicate that during the 2000 ablation season at least 30% of the load at the lower gauging station on North Proglacial Stream was entrained from the proglacial area. On Central Proglacial Stream this ratio was closer to 80%. This variation between streams was most likely the result of differences in sediment availability within the proglacial channels, differences in glacial input of sediment and discharge and variation in inputs from extrachannel surfaces. However, the results clearly indicate that the proglacial channels at Small River Glacier were functioning as a significant store and source of suspended sediment. Storage and release of sediment in proglacial channels is therefore likely to play a significant role in modifying suspended sediment transfer patterns from glacierized basins.

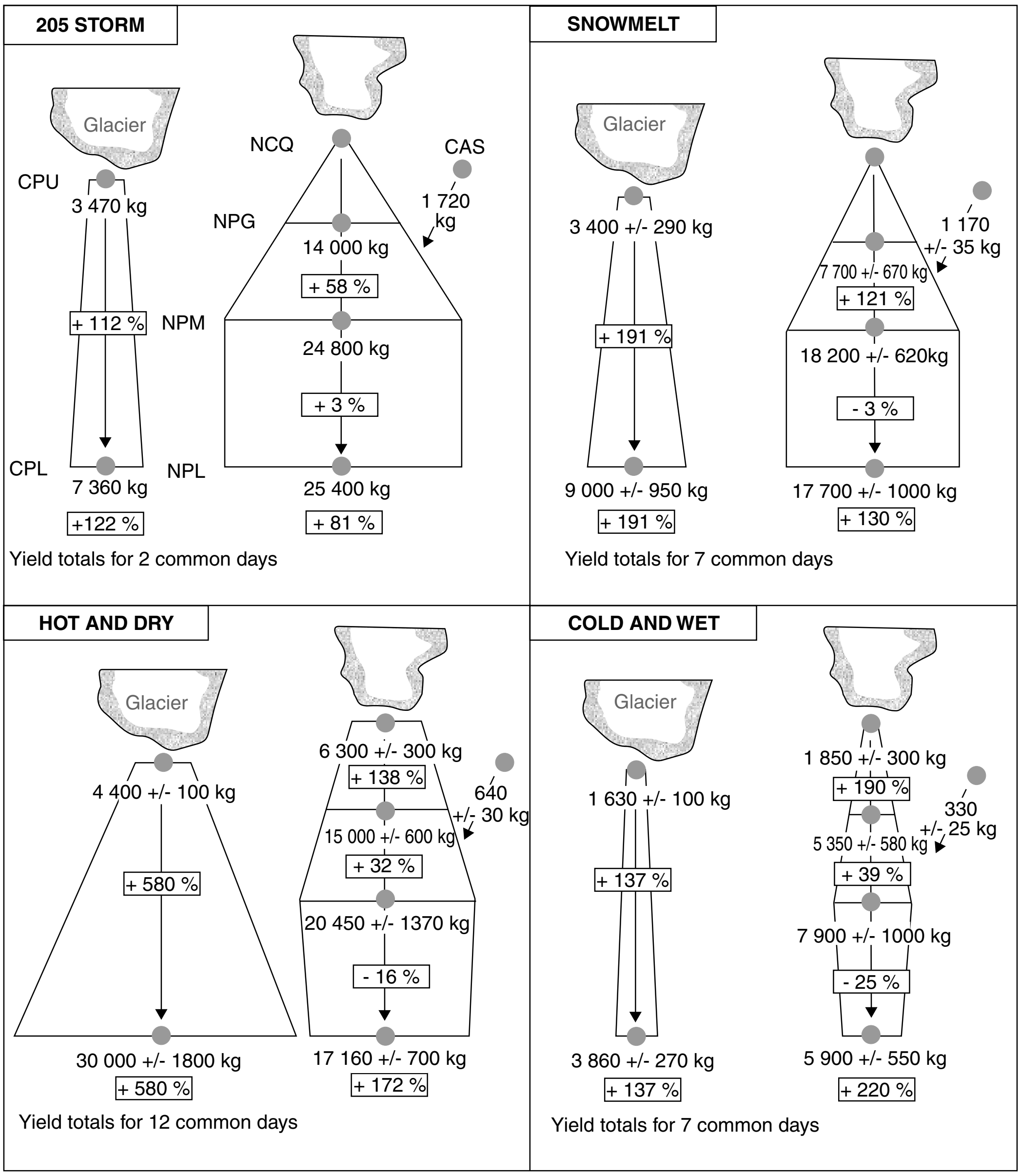

Figure 10. Proportional figures of suspended sediment yield from representative common days for each meteorological period. Note the significant spatial variability in yield response as determined by different catchment locations and meteorological conditions. Filled circles represent the gauging stations shown in Figure 1. Central Proglacial Middle and North gauging stations are not shown

IMPLICATIONS AND CONCLUSIONS

The proglacial control on suspended sediment transfer patterns revealed in this study has implications for the interpretation of suspended sediment yield from glacierized basins. Previous research has often assumed that elevated suspended sediment yields from glacierized basins are an indication of direct glacial denudation rates (e.g. Hallet *et al*., 1996). As these rates are elevated compared with those from non-glacial basins, they have been used as evidence for the increased efficacy of glacial erosion. However, it has been argued that a reliable relationship between glacial and non-glacial erosion rates on the basis of sediment yield has not yet been determined, with recognition that storage and release of sediment in proglacial channels may play a significant role in controlling these yield patterns (e.g. Warburton, 1990; Harbor and Warburton 1993). The results from Small River confirmed that the proglacial area, and in particular proglacial channels, can control suspended sediment yield patterns and that those patterns vary both spatially and temporally.

The spatial and temporal variability of transfer patterns at Small River Glacier clearly showed that the location of a gauging station will determine the pattern of sediment transfer observed and have a significant influence on the interpretation of those patterns. However, the relative importance of single or multiple gauging stations for interpreting the proglacial channel control on suspended sediment transfer patterns will depend on the focus of the research. For example, if the focus is to simply determine the net amount of suspended sediment being transferred from a basin, irrespective of source, a single gauging station at the exit of the basin is likely to be sufficient (e.g. Collins, 1998). However, if the aim of the study is to interpret the relative roles of sediment sources and transfer processes within a glacierized basin, or to use sediment yields as a measure of direct glacial denudation, then multiple gauging sites with high-frequency monitoring of suspended sediment concentration will be necessary in order to characterize the effect of proglacial channel sediment storage and release on transfer patterns.

If modification of sediment transfer patterns by proglacial channel sediment storage and release is the general case, this effect will increase with distance from the active glacial/proglacial area (Warburton, 1999). This is because the potential for sediment storage in fluvial channels and valley floors increases with basin size (Slaymaker, 1987). However, suspended sediment yield patterns observed at a distance from contemporary proglacial areas will be further confounded by the inheritance of sediment from previous glacial events stored in fluvial systems and on land surfaces (e.g. Jordan and Slaymaker, 1991; Brooks, 1994). For example, data from British Columbia showed that suspended sediment yield increased at all spatial scales, contrary to the conventional model that sediment yield decreases with basin area (Church and Slaymaker, 1989; Ashmore, 1993). This increase was attributed to remobilization of sediment delivered by glacial events more than 10 000 years ago (Church and Slaymaker, 1989; Church *et al*., 1999). Thus downstream patterns will reflect not only components of contemporary transfer from active proglacial areas but also the reworking of Pleistocene deposits. Determining the relative contribution of these sources therefore becomes extremely difficult (Jordan and Slaymaker, 1991). It would seem difficult therefore to establish accurate contemporary glacial denudation rates from suspended sediment yields unless these storage effects can be accurately determined and adjusted for.

The experimental design and multivariate statistic approach (Hannah *et al*., 2000) used in this study provided an objective characterization of the proglacial control on suspended sediment transfer patterns. The multivariate statistical approach was particularly useful in 'reducing' large data sets to a manageable size, maintaining as much of the data structure as possible. Use of this method was successful in characterizing the 'shape' and 'magnitude' response of each gauging site's suspended sediment record. Combining the 'shape' and 'magnitude' classifications with meteorological data allowed segregation of spatial and temporal suspended sediment response patterns. Furthermore, the statistical method was consistent in assigning classes that had similar spatial process significance (e.g. rainfall events). Because of this consistency, this method can be used to identify seasonal and downstream changes in proglacial suspended sediment transfer patterns. This provides a useful means of linking proglacial suspended sediment response to generating forces. Further application of this spatially distributed monitoring approach and analysis technique to other proglacial areas would better establish the proglacial channel control on suspended sediment yield patterns from glacierized basins.

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