Variability in Stream Erosion and Sediment Transport (Proceedings of the Canberra Symposium, December 1994). IAHS Publ. no. 224, 1994.

Water and sediment discharge from glacier basins: an arctic and alpine comparison

A. M. GURNELL
School of Geography, University of Birmingham, Birmingham B15 2TT, UK

A. HODSON, M. J. CLARK
Department of Geography, University of Southampton, Southampton SO9 5NH, UK

J. BOGEN, J. O. HAGEN
Norwegian Water Resources and Energy Administration, PO Box 5091, Majorstua, N-0806 Oslo, Norway

M. TRANTER
Department of Geography, University of Bristol, Bristol BS8 1SS, UK

Abstract This paper compares the discharge and the dissolved and suspended sediment transport from two glacier basins: the Haut Glacier d'Arolla basin, Valais, Switzerland and Austre Brøggerbreen basin, Svalbard. Information from the two basins has been split into subperiods to represent different components of the ablation season. Three differences are identified between the magnitude and timing of flow and sediment transport components: (a) in the alpine basin, discharge follows a distinct seasonal sequence which is driven by the balance between direct solar radiation input and reflected radiation from a glacier surface of progressively changing albedo. Although a similar ablation season sequence is identifiable for the arctic basin, it is relatively subdued and heavily modified by the influence of advected energy on melt rates; (b) the solute concentrations in the meltwater of the rivers in both environments (as described by continuous monitoring of electrical conductivity), also shows a distinct pattern through the ablation season, but the diurnal variations observed in the alpine environment, which have been attributed to either the mixing of runoff components or variability in the nature of the weathering environment, are not present in the arctic record; (c) the widely-reported "exhaustion" in suspended sediment supply to alpine proglacial streams over the summer ablation season is not evident in the arctic basin. Indeed, increased supply of suspended sediment may occur through the arctic ablation season.

INTRODUCTION

Whilst much research has been focused upon the hydrology of alpine glaciers, arctic glacier hydrology has received considerably less attention. The arctic environment provides great potential for hydrological study because there is a complex range of potential ground and ice temperature conditions (e.g. Blatter & Hutter, 1991) which have additional and complex influences on hydrological processes in addition to the seasonal movement of the snow line, the associated change in glacier albedo, and the resultant change in the amount and routing of meltwater to the proglacial river that supports the typical seasonal hydrological pattern in alpine glacier basins (Röthlisberger & Lang, 1987).

This paper contrasts time series of discharge, suspended sediment concentration and electrical conductivity from the proglacial rivers draining a warm-based alpine glacier and a polythermal sub-polar glacier of similar size. Information from two ablation seasons for each basin may well be unrepresentative of the longer-term character of the basins, but the differences in the records are sufficiently marked to illustrate some of the impacts of climatic and ice temperature gradients on the regime of proglacial rivers.

THE STUDY AREA AND DATA COLLECTION

Austre Brøggerbreen (an arctic glacier) is located some 3 km to the southwest of Ny-Alesund, northwest Svalbard. It has an area of approximately 11.7 km^2 rising from approximately 50 m at the snout to 720 m above sea level at the watershed. Meltwater drains to Kongsfiord via the Bayelva River. The bedrock consists of Devonian, Carboniferous and Tertiary sedimentary rocks which include limestone, dolomite, shale and red sandstones. The glacier has retreated considerably over the last 100 years. Maximum ice thickness is currently approximately 130 m and the glacier base is polythermal, being warm beneath ice thicknesses in excess of 70-80 m and cold beneath shallower ice (Hagen *et al.*, 1991). The catchment receives continuous daylight from 18 April to 24 August, although frequent periods of coastal fog and high cloud cover strongly influence the receipt of direct solar radiation (Hodson *et al.*, in preparation).

Haut Glacier d'Arolla (an alpine glacier) is located in the Val d'Herens, Switzerland, and has an area of approximately 6.3 km^2. The glacier ranges in altitude from 2560 m at the snout to 3838 m at the watershed. The glacier has been retreating in recent years, is warm-based and has a maximum ice thickness of approximately 180 m (Sharp *et al.*, 1993). The catchment is underlain by schists and gneisses of the Arolla series. Snow and ice melt is strongly influenced by diurnal variations in incident solar radiation (Gurnell *et al.*, 1992a).

This paper reports on variations in the discharge, electrical conductivity and suspended sediment concentration of the proglacial rivers draining the two study catchments over two ablation seasons: 1989 and 1990 for the Haut Glacier d'Arolla catchment and 1991 and 1992 for the Austre Brøggerbreen catchment. The field monitoring periods for the Haut Glacier d'Arolla extended from early June to early September in both years, whereas the shorter field seasons for the Austre Brøggerbreen extended from late June to mid-August in 1991 and to early August in 1992. The timing of the monitoring periods is summarized in Table 1. They include the phase of snowmelt from the glacier foreland and extend well into the phase dominated by melt from the glaciated portion of the catchment in all of the four field seasons. In both catchments the electrical conductivity and suspended sediment concentration of the proglacial river were monitored within 200 m of the glacier snout. Electrical conductivity and water temperature were monitored using a pHOX 57 (Mk 2) conductivity and water temperature recorder. The conductivity data were recorded at the ambient water temperature which was always in the range 0-2°C. Suspended sediment concentration was estimated by filtration of water samples collected at two and three hourly intervals in Switzerland and Svalbard, respectively, using an ISCO automatic pump sampler. The

Table 1 The timing of the subperiods identified for each of the four ablation season data sets.

	Period	Start date	End date
Haut Glacier d'Arolla 1989	1	1 June	8 June
	2	9 June	15 June
	3	16 June	8 July
	4	9 July	6 August
	5	7 August	31 August
Haut Glacier d'Arolla 1990	1	29 May	19 June
	2	19 June	2 July
	3	2 July	27 July
	4	27 July	13 August
	5	13 August	26 August
Austre Brøggerbreen 1991	1	27 June	3 July
	2	4 July	14 July
	3	15 July	5 August
	4	6 August	14 August
Austre Brøggerbreen 1992	1	24 June	3 July
	2	4 July	10 July
	3	11 July	16 July
	4	17 July	22 July
	5	23 July	28 July
	6	29 July	3 August

water samples were filtered through Whatman 40 (Switzerland) and Whatman 0.45 μm cellulose nitrate (Svalbard) filter papers. In Switzerland, these suspended sediment concentration determinations were used to calibrate a continuous turbidity record, monitored using a Partech 7000 series model 3RP suspended solids monitor fitted with a single head probe (Gurnell *et al.*, 1992b), to derive an hourly time series of suspended sediment concentration estimates. Lower suspended sediment concentrations and consequent interference from ambient light precluded a similar approach in Svalbard.

In Svalbard, discharge was monitored at the same site as electrical conductivity and suspended sediment concentration by developing a discharge rating relationship between current-metered discharge estimates and water stage monitored by pressure transducer. Although a relatively stable river section was used for discharge monitoring, it is likely that errors associated with the discharge estimates are at least 10% (Hodson, 1994). In Switzerland, hourly determinations of discharge were provided by the Grande Dixence hydropower company who monitor flow at a rectangular sharp-crested weir structure located approximately 1 km from the glacier snout. There are no significant inputs of water to the river between the water quality monitoring site and the Grande Dixence gauging station.

Thus, in summary, hourly determinations of electrical conductivity and discharge were available for two field seasons from both glacier basins. In addition, hourly estimates of suspended sediment concentration were available for two seasons for the Haut Glacier d'Arolla, and three hourly determinations were available for only one season (1992) for the Austre Brøggerbreen basin.

DATA ANALYSIS

The proglacial discharge, electrical conductivity and suspended sediment concentration time series monitored during the four periods were subjected to similar analyses in order to allow comparison of the two study catchments. Each field season was split into "hydrologically-meaningful" subperiods which could be analysed and compared. In the case of the Haut Glacier d'Arolla, this subdivision was achieved by identifying periods of similar magnitude and diurnal variability in discharge (Gurnell *et al.*, 1991; Gurnell *et al.*, 1992a), which is a measure of the amount, storage and routing of meltwater (Gurnell, 1993; Röthlisberger & Lang, 1987). These latter factors affect the degree to which the meltwater has access to sources of suspended sediment and solutes. Five subperiods were identified in each of the 1989 and 1990 data sets (Table 1). In the case of the Austre Brøggerbreen catchment, subperiods were isolated on the basis of patterns identified within time series of hourly observations of solar radiation receipt, wind direction and air temperature (Hodson *et al*, in preparation). This approach was adopted because of the substantial influence of advected energy (represented by the wind direction and air temperature) on melt rates, in addition to the influence of direct solar radiation receipt. Four and six subperiods were identified for the 1991 and 1992 field seasons, respectively (Table 1). Splitting ablation season river flow data into subperiods prior to analysis is consistent with the approach adopted in analysing similar alpine glacier-basin data (Jensen & Lang, 1973; Lang & Dayer, 1985). The following three groups of analyses were applied to the data sets for each subperiod: *firstly,* the lags or leads between the time series were estimated; *secondly,* suspended sediment concentration and conductivity-discharge relationships were estimated between the series using linear regression analysis after lagging the series to their best match position; and *finally,* Box & Jenkins (1976) ARIMA models were estimated for each of the time series.

Table 2 provides a first indication of the changing relationships between the monitored time series at a seasonal and sub-seasonal level and also some differences between the relationships in the two study basins. In all cases the discharge and suspended sediment concentration series were $\log_{10}$ transformed to stabilize the variance in the individual series and to generate the most linear relationship between the series. The best match position between each pair of time series was then identified from the cross correlation function estimated between the series.

Table 3 lists the parameters of the simple linear regression relationships estimated between the lagged electrical conductivity or suspended sediment concentration series and the discharge series. A subdivision of periods 3 and 2 in 1989 and 1990, respectively, at Haut Glacier d'Arolla was necessary prior to estimating the relationship between electrical conductivity and discharge.

Table 4 lists the form and parameters of the ARIMA models estimated for each of the time series. The approach adopted for model identification, estimation and diagnostic checking is described in Gurnell *et al.* (1992a). In each case, the parameters of the models are all significantly different from zero ($P < 0.05$) and the residuals represent white noise once the time series has been filtered by the ARIMA model (i.e. there was no identifiable temporal pattern remaining in the residuals as indicated by the autocorrelation function (acf) and partial autocorrelation function (pacf) for the residual series and by a Portmanteau χ^2 test applied to the first 24 autocorrelations of the residual series (acf).

RESULTS

Two major trends can be identified from Table 2: the lags/leads of the alpine series are much shorter than those of the arctic series; and there is a clear seasonal trend in the lags/leads for both environments. The difference in lags/leads suggests major contrasts in the functioning of glacier hydrological processes in both environments. In the alpine system, it has been suggested that meltwater is routed through a series of reservoirs whose size and residence time change throughout the ablation season (Gurnell, 1993). The residence time of meltwater in contact with rock debris influences the solute load of the meltwater, and an inverse relationship between solute concentration and discharge is induced by the mixing of meltwaters draining reservoirs in different locations and with different residence times (e.g. Brown & Tranter, 1990). The best match positions indicated by the cross correlation functions between the series (Table 2) all indicate a negative relationship between electrical conductivity (a surrogate for varying solute concentration) and discharge, but the longer and more variable lags from the arctic basin suggests that other major influences may be operating. Whilst there are very small lags

Table 2 Best match position between raw time series (identified from cross correlation functions).

Input	Output	Time period: 1	2	3	4	5	6	Direction of correlation
		(Time (h) of best match)						
Haut Glacier d'Arolla: 1989								
$\log_{10} Q$	cond	*	−1	−1	−1	−2		−
$\log_{10} Q$	$\log_{10} S$	*	0	0	+2	0		+
Haut Glacier d'Arolla: 1990								
$\log_{10} Q$	cond	0	0	−1	−1	−1		−
$\log_{10} Q$	$\log_{10} S$	*	0	0	0	0		+
Austre Brøggerbreen: 1991								
$\log_{10} Q$	cond	*[1]	+2	+3	+4			−
Austre Brøggerbreen: 1992								
$\log_{10} Q$	cond	*	+2	0	+3	+2	0	−
$\log_{10} Q$	$\log_{10} S$	*	−6	−5	−5	−2	−1	+

Q – discharge; S – suspended sediment concentration; cond – electrical conductivity.
* No clearly defined best match position.
*[1] The time series for period 1, 1991, are short with many missing values.

between the positively correlated suspended sediment and discharge series for the alpine basin, the suspended sediment series leads the discharge series in the arctic basin, and the lead decreases through the ablation season. This could suggest a difference between the source areas of suspended sediment and discharge in both systems, with the suspended sediment sources being located closer to the monitoring site, (but with some convergence in the locations of the sediment and meltwater sources as the ablation season progresses) in the arctic system.

The linear regression relationships in Table 3 are estimated after lagging to the best match positions. Lagging removes some of the hysteresis in the relationship between the series, but significant hysteresis remains so that the residuals from the estimated regression relationships will be significantly serially autocorrelated. Nevertheless, trends in the regression intercepts and slopes provide a useful description of broad adjustments in the relationships between the variables throughout the ablation season (Table 3). The following generalizations can be made: *firstly*, the relationships between time series are stronger (as indicated by the coefficient of determination) for the alpine than the arctic basin; *secondly,* the intercepts and slopes of the conductivity-discharge relationships are similar although slightly steeper for the alpine in comparison with the arctic basin, and *finally* the alpine suspended sediment concentration-discharge relationships are weak in period 1, are steepest and strongest in period 2 and then stabilize at an intermediate slope for the remainder of the ablation season, whereas the arctic relationships exhibit an increasing slope as the ablation season progresses.

Many of the estimated ARIMA models in Table 4 have a "seasonal" component which reflects the impact of diurnal variations in incident solar radiation on the hydrology of both the arctic and alpine glaciers. In both arctic and alpine basins, the ARIMA models estimated for the discharge series develop a diurnal component as the ablation season progresses, and the form of the ARIMA models is very similar between the two basins. However, there are differences between the two basins. *Firstly,* the very strong short-term autoregressive components in the alpine sediment models (with AR1 and AR2 components in many cases) are not as clear in the arctic example (only an AR1 component present) and, furthermore, the diurnal component of the arctic ARIMA models is usually accommodated simply by seasonal differencing, whereas there is also a seasonal MA component for the alpine basin. *Secondly*, the electrical conductivity ARIMA models for the alpine basin virtually all have a diurnal component, but this is rarely the case for the arctic basin.

DISCUSSION AND CONCLUSIONS

From the above results, it is possible to identify the following differences between the hydrology of the arctic (Austre Brøggerbreen) and alpine (Haut Glacier d'Arolla) glacier basins:

(a) Proglacial discharge exhibits clear diurnal variations in response to solar radiation inputs in both basins. These diurnal variations can be represented by time series models of very similar form in both environments and the diurnal rhythm in the discharge record strengthens as the ablation season progresses.

(b) Suspended sediment concentrations also exhibit clear diurnal variations in both environments, but the diurnal influence (as represented by the forms of the estimated ARIMA models) is stronger in the alpine than in the arctic environment. The

Table 3 Simple regression relationships estimated between electrical conductivity/$\log_{10}$ suspended sediment concentration and $\log_{10}$ discharge at the best temporal match position.

Dependent variable (lag in h)	Independent variable	Period	a	t_a	b	t_b	n	R^2
Haut Glacier d'Arolla: 1989								
cond (0)	$\log_{10} Q$	1	108.7	42.8	−27.6	30.3	193	0.827
cond (+1)	$\log_{10} Q$	2	96.0	109.1	−23.9	86.2	139	0.982
cond (+1)	$\log_{10} Q$	3A	83.9	91.5	−20.3	71.2	245	0.954
cond (+1)	$\log_{10} Q$	3B	75.9	32.5	−17.1	24.7	236	0.722
cond (+1)	$\log_{10} Q$	4	83.3	66.5	−18.3	51.1	628	0.806
cond (+2)	$\log_{10} Q$	5	74.0	44.7	−15.7	33.8	381	0.751
$\log_{10} S$ (0)	$\log_{10} Q$	1	1.75	6.6	0.31	3.2	137	0.072
$\log_{10} S$ (0)	$\log_{10} Q$	2	−0.15	0.6	0.86	11.7	116	0.545
$\log_{10} S$ (0)	$\log_{10} Q$	3	−3.95	28.4	1.98	47.2	506	0.815
$\log_{10} S$ (−2)	$\log_{10} Q$	4	−0.87	5.2	1.09	22.9	658	0.445
$\log_{10} S$ (0)	$\log_{10} Q$	5	−1.07	7.3	1.21	29.2	490	0.443
Haut Glacier d'Arolla: 1990								
cond (0)	$\log_{10} Q$	1	90.1	160.7	−22.7	115.7	492	0.965
cond (0)	$\log_{10} Q$	2A	69.0	58.6	−15.9	44.4	196	0.910
cond (0)	$\log_{10} Q$	2B	73.5	22.8	−15.5	16.9	110	0.724
cond (+1)	$\log_{10} Q$	3	99.2	58.2	−23.0	47.5	527	0.811
cond (+1)	$\log_{10} Q$	4	85.2	43.2	−19.1	33.8	323	0.780
cond (+1)	$\log_{10} Q$	5	81.7	56.1	−18.1	42.3	290	0.861
$\log_{10} S$ (0)	$\log_{10} Q$	1	−1.16	6.8	1.10	18.6	390	0.471
$\log_{10} S$ (0)	$\log_{10} Q$	2	−5.21	30.0	2.39	46.4	310	0.875
$\log_{10} S$ (0)	$\log_{10} Q$	3	−0.27	1.9	0.95	23.0	550	0.490
$\log_{10} S$ (0)	$\log_{10} Q$	4	−0.87	3.8	1.18	18.4	288	0.541
$\log_{10} S$ (0)	$\log_{10} Q$	5	−0.27	1.1	1.07	32.8	290	0.789
Austre Brøggerbreen: 1991								
cond (0)	$\log_{10} Q$	1	no significant relationship					
cond (−2)	$\log_{10} Q$	2	84.6	33.9	−18.1	20.1	92	0.816
cond (−3)	$\log_{10} Q$	3	41.9	21.2	−7.2	11.6	515	0.208
cond (−4)	$\log_{10} Q$	4	54.5	15.0	−12.0	10.8	144	0.450
Austre Brøggerbreen: 1992								
cond (0)	$\log_{10} Q$	1	161.1	14.6	−41.9	12.7	184	0.470
cond (−2)	$\log_{10} Q$	2	26.6	33.4	−3.8	14.7	155	0.585
cond (0)	$\log_{10} Q$	3	33.6	31.4	−5.8	16.3	68	0.799
cond (−3)	$\log_{10} Q$	4	63.2	18.6	−14.6	13.8	132	0.593
cond (−2)	$\log_{10} Q$	5	57.6	17.6	−12.7	13.1	123	0.584
cond (0)	$\log_{10} Q$	6	64.4	36.7	−14.2	28.3	114	0.876
$\log_{10} S$ (0)	$\log_{10} Q$	1	−0.36	0.4	0.73	2.3	64	0.078
$\log_{10} S$ (+6)	$\log_{10} Q$	2	−0.05	0.2	0.60	6.4	53	0.444
$\log_{10} S$ (+5)	$\log_{10} Q$	3	−0.48	1.4	0.75	7.0	44	0.535
$\log_{10} S$ (+5)	$\log_{10} Q$	4	−2.89	4.2	1.47	6.9	44	0.528
$\log_{10} S$ (+2)	$\log_{10} Q$	5	−4.18	3.5	1.80	5.1	46	0.368
$\log_{10} S$ (+1)	$\log_{10} Q$	6	−3.54	3.8	1.68	6.2	44	0.476

Q: discharge in l s^{-1}; S: suspended sediment concentration in mg l^{-1}; cond: electrical conductivity in $\mu S\ cm^{-1}$.
a: regression intercept and t statistic (t_a); b: regression slope and t statistic (t_b).

steepest and strongest linear regression relationships between suspended sediment concentration and discharge occur relatively early in the ablation season in the alpine basin and, thereafter, lower suspended sediment concentrations are associated with given levels of discharge, suggesting a degree of exhaustion in the supply of

Table 4 ARIMA models estimated from the river time series – all models listed have parameters which are significantly different from zero ($P < 0.05$) and reduce the original time series to white noise.

Variable	Time period	ARIMA model	ARIMA parameters: 1	2	3	4	Constant (if est.)
Haut Glacier d'Arolla: 1989							
$\log_{10} Q$	1	(1,1,0)	−0.29				
	2	$(1,1,0)(0,1,1)_{24}$	0.38	0.56			
	3	$(1,1,0)(0,1,1)_{24}$	0.53	0.82			
	4	$(2,1,0)(0,1,1)_{24}$	0.24	−0.18	0.81		
	5	$(2,1,0)(0,1,1)_{24}$	0.18	−0.23	0.76		
cond	1	(1,1,0)	0.34				
	2	$(1,1,0)(0,1,1)_{24}$	0.56	0.41			
	3	$(1,1,0)(0,1,1)_{24}$	0.42	0.42			
	4	$(1,1,0)(0,1,1)_{24}$	0.12	0.73			
	5	$(0,1,0)(0,1,1)_{24}$	0.64				
$\log_{10} S$	1	(0,1,1)	0.57				
	2	(0,1,1)	0.26				
	3	$(2,0,0)(0,1,1)_{24}$	0.77	0.16	0.76		
	4	$(2,0,0)(0,1,1)_{24}$	0.67	0.24	0.85		
	5	$(2,0,0)(0,1,1)_{24}$	0.59	0.25	0.68		
Haut Glacier d'Arolla: 1990							
$\log_{10} Q$	1	$(1,1,0)(0,1,1)_{24}$	0.80	0.77			
	2	$(1,1,0)(0,1,1)_{24}$	0.46	0.81			
	3	$(1,1,0)(0,1,1)_{24}$	0.51	0.71			
	4	$(1,1,0)(0,1,1)_{24}$	0.15	0.68			
	5	$(2,1,0)(0,1,1)_{24}$	0.33	−0.35	0.48		
cond	1	$(1,1,0)(0,1,1)_{24}$	0.77	0.86			
	2	$(1,1,0)(0,1,1)_{24}$	0.41	0.83			
	3	$(2,1,0)(0,1,2)_{24}$	0.33	−0.29	0.83	−0.16	
	4	$(2,1,0)(0,1,1)_{24}$	0.05	−0.31	0.94		
	5	$(2,1,0)(0,1,1)_{24}$	0.22	−0.32	0.63		
$\log_{10} S$	1	$(2,0,0)(0,1,1)_{24}$	0.64	0.24	0.69		
	2	$(2,0,0)(0,1,1)_{24}$	0.74	0.21	0.62		
	3	$(2,0,0)(0,1,1)_{24}$	0.57	0.25	0.81		
	4	$(1,0,0)(0,1,1)_{24}$	0.62	0.74			
	5	$(2,0,0)(0,1,1)_{24}$	0.45	0.19	0.65		
Austre Brøggerbreen: 1991							
$\log_{10} Q$	1*	(1,0,0)	0.95				0.15
	2	(2,1,0)	0.42	0.38			
	3	$(1,1,0)(0,1,1)_{24}$	0.20	0.95			
	4	$(1,1,0)(0,1,1)_{24}$	0.53	0.83			
cond	1*	(1,1,0)	0.97				
	2	(2,1,0)	0.58	0.23			
	3	no satisfactory model estimated					
	4	(2,1,0)	0.61	−0.25			
Austre Brøggerbreen: 1992							
$\log_{10} Q$	1	$(0,1,0)(1,1,0)_{24}$	0.64				
	2	$(1,1,0)(0,1,1)_{24}$	0.50	0.85			
	3	$(1,1,0)(0,1,1)_{24}$	0.63	0.60			
	4	$(1,1,0)(0,1,1)_{24}$	0.42	0.76			
	5	$(1,1,0)(0,1,1)_{24}$	0.70	0.72			
	6	$(1,1,0)(0,1,1)_{24}$	0.50	0.42			
cond	1	$(0,1,0)(1,1,0)_{24}$	−0.33				
	2	(2,1,0)	0.45	0.22			
	3	(2,1,0)	0.47	0.34			
	4	(2,1,0)	0.48	0.25			
	5	(2,1,0)	0.46	0.28			
	6	(1,1,0)(0,1,1)	0.51	−0.68			
$\log_{10} S$	1	$(1,0,0)(1,1,0)_8$	0.45	−0.43			
	2	$(0,0,0)(1,1,0)_8$	0.33				
	3	$(1,0,0)(0,1,0)_8$	0.78				
	4	$(1,0,0)(0,1,0)_8$	0.58				
	5	$(1,0,0)(0,1,0)_8$	0.65				
	6	(1,0,0)	0.80				0.46

The seasonal ARIMA models relate to 24 h periods which are represented by 24 observations for all series apart from Austre Brøggerbreen 1992 $\log_{10} S$ series which has eight observations in each 24 h "season".
* ARIMA models for period 1, 1991, are estimated from short time series with many missing values.

sediment to the proglacial river (Gurnell, 1987). In contrast, the linear regression relationships steepen through the ablation season in the arctic basin. Furthermore, where there is a short or negligible lag/lead between the suspended sediment and discharge series in the alpine basin, suspended sediment concentrations lead discharge by 6 h, falling to 1 h through the 1992 observation period in the arctic basin. The steepening linear regression relationships estimated for the arctic basin confirm the apparent increase in suspended sediment availability that has been described elsewhere (Bogen, 1991) and has been attributed to the development of a subglacial drainage network (Repp, 1988). As the ablation season progresses, meltwater is generated initially from predominantly proglacial snowmelt sources and then increasingly from glacial snowmelt and icemelt sources. The decreasing lead of suspended sediment concentration in comparison with the discharge record may indicate an even more pronounced up-glacier migration of the predominant suspended sediment sources from proximal locations to increasingly distal glacial (subglacial, supraglacial and ice marginal) locations, and thus could reinforce the potentially increasing role of subglacial drainage. However, in arctic basins sediment availability is only partly governed by meltwater-sediment contact. The temperature regime of the sediment is also important and so increasing sediment availability and decreasing sediment lead times could also indicate the significance of spatially and temporally variable ground thaw processes.

(c) The linear regression relationships estimated between electrical conductivity and discharge are very similar, although the arctic relationships are not quite as steep or strong as the alpine ones for the two environments, illustrating the widely-recognized inverse relationship (Fenn, 1987). In alpine environments a variety of mechanisms have been suggested to explain this inverse relationship including the mixing of waters from different conceptual reservoirs (e.g. Brown & Tranter, 1990) and the increasing residence time of water draining from single reservoirs under recession flows (e.g. Souchez & Lemmens, 1987). The inverse relationships identified for alpine environments have been noted at a variety of timescales, with the very strong inverse pattern between electrical conductivity and discharge at the diurnal timescale (e.g. Gurnell *et al.*, in press) being emphasized as an indicator of the mixing of fast-transit, supraglacial meltwaters with longer-residence subglacial water. The analysis presented in this paper suggests that it is longer-term patterns which are most influential in the inverse relationship between electrical conductivity and discharge in the arctic basin. The ARIMA models estimated for the arctic electrical conductivity time series rarely exhibited a significant "seasonal" (diurnal) component, and the cross-correlation functions estimated between discharge and electrical conductivity did not exhibit the strong diurnal pattern of those estimated from the alpine basin time series. This suggests that the meltwater mixing processes that have received so much research attention in the alpine environment (Fenn, 1987), are less significant or operate at a different timescale in the arctic basin. Given the cold-base of much of the arctic glacier, this is hardly surprising, since the interaction between longer-residence high-solute subglacial waters (from the warm-based section of the glacier?) and shorter-residence low-solute waters will be difficult and there may be substantial time delays before the impact of the diurnal melt cycle (which is weaker than its alpine equivalent) on such mixing can be observed at a proglacial monitoring site.

Acknowledgements The alpine research was supported by a Natural Environment Research Council (NERC) research grant (GR3/7004). The arctic research was given logistical and financial support by Norsk Polarinstitutt and the work of A. Hodson was funded by an NERC research studentship.

REFERENCES

Bogen, J. (1991) Erosion and sediment transport in Svalbard. In: *Arctic Hydrology: Present and Future Tasks* (ed. by Y. Gjessing, J. O. Hagen, K. A. Hassel, K. Sand, & B. Wold). Norwegian Committee for Hydrology, Oslo.

Box, G. E. P. & Jenkins, G. M. (1976) *Time Series Analysis, Forecasting and Control*, revised edition. Holden-Day, San Francisco.

Blatter, H. & Hutter, K. (1991) Polythermal conditions in arctic glaciers. *J. Glaciol.* **37**, 261-269.

Brown, G. H. & Tranter, M. (1990) Hydrograph and chemograph separation of bulk meltwaters draining the Upper Arolla Glacier, Valais, Switzerland. In: *Hydrology in Mountain Regions.* I — *Hydrological Measurements; The Water Cycle* (ed. by H. Lang & A. Musy) (Proc. two Lausanne Symposia, August 1990), 429-437. IAHS Publ. no. 193.

Fenn, C. R. (1987) Electrical conductivity. In: *Glacio-fluvial Sediment Transfer: An Alpine Perspective* (ed. by A. M. Gurnell & M. J. Clark), 377-414. Wiley, Chichester, UK.

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

Gurnell, A. M. (1993) How many reservoirs? An analysis of flow recessions from a glacier basin. *J. Glaciol.* **39**, 409-414.

Gurnell, A. M., Brown, G. H. & Tranter, M. (in press) A sampling strategy to describe the temporal hydrochemical characteristics of an alpine proglacial stream. *Hydrol. Processes.*

Gurnell, A. M., Clark, M. J. & Hill, C. T. (1992a) Analysis and interpretation of patterns within and between hydroclimatological time series in an Alpine glacier basin. *Earth Surf. Processes and Landforms* **17**, 821-839.

Gurnell, A. M., Clark, M. J., Hill, C. T. & Greenhalgh, J. (1992b) Reliability and representativeness of a suspended sediment concentration monitoring programme for a remote alpine proglacial river. In: *Erosion and Sediment Monitoring Programmes in River Basins* (ed. by J. Bogen, D. E. Walling & T. J. Day) (Proc. Oslo Symp., August 1992), 191-200. IAHS Publ. no. 210.

Gurnell, A. M., Clark, M. J., Tranter, M., Brown, G. H. & Hill, C. T. (1991) Alpine glacier hydrology inferred from a proglacial river monitoring programme. *Proc. British Hydrological Society National Symposium*, 5.9-5.16.

Hagen, J. O., Korsen, O. M. & Vatne, G. (1991) Drainage pattern in a subpolar glacier: Brøggerbreen, Svalbard. In: *Arctic Hydrology: Present and Future Tasks* (ed. by Y. Gjessing, J. O. Hagen, K. A. Hassel, K. Sand & B. Wold), 121-131. Norwegian Committee for Hydrology, Oslo.

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

Hodson, A., Gurnell, A. M., Bogen, J., Clark, M. J., Hagen, J. O. & Tranter, M. (in preparation) Patterns in hydroclimatological time series in a sub-polar glacier basin.

Jensen, H. & Lang, H. (1973) Forecasting discharge from a glaciated basin in the Swiss Alps. In: *Role of Snow and Ice in Hydrology* (Proc. Banff Symposia, September 1972), vol. 2, 1047-1054. IAHS Publ. no. 107.

Lang, H. & Dayer, G. (1985) Switzerland case study: water supply. In: *Techniques for the Prediction of Runoff from Glacierized Areas* (ed. by G. Young), 45-57. IAHS Publ. no. 149.

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

Röthlisberger, H. & Lang, H. (1987) Glacial hydrology. In: *Glacio-fluvial Sediment Transfer: An Alpine Perspective* (ed. by A. M. Gurnell & M. J. Clark), 207-284. Wiley, Chichester, UK.

Sharp, M., Richards, K., Willis, I., Arnold, N., Nienow, P., Lawson, W. & Tison, J. L. (1993) Geometry, bed topography and drainage system structure of the Haut Glacier d'Arolla, Switzerland. *Earth Surf. Processes and Landforms* **18**, 557-571.

Souchez, R. A. & Lemmens, M. M. (1987) Solutes. In: *Glacio-fluvial Sediment Transfer: An Alpine Perspective* (ed. by A. M. Gurnell & M. J. Clark), 285-303. Wiley, Chichester, UK.