The influence of supraglacial debris on proglacial runoff fluctuations and water chemistry

Fyffe, C. L.[1], Brock, B. W.[2], Kirkbride, M. P.[3], Black, A. R.[3], Smiraglia, C.[4], Diolaiuti. G.[4]

[1] **c.fyffe@worc.ac.uk,** Institute of Science and the Environment, University of Worcester, Worcester, United Kingdom, [2] Department of Geography, Northumbria University, Newcastle, United Kingdom, [3] School of the Environment, University of Dundee, Dundee, United Kingdom and [4] Department of Earth Sciences 'Ardito Desio', University of Milan, Milan, Italy

1. Introduction

This study explores how the debris' influence on glacial ablation, topography and drainage structure impacts on the water chemistry and runoff signal of the proglacial stream. This was achieved through analysis of the supraglacial and proglacial water chemistry and the proglacial hydrograph of Miage Glacier, Western Italian Alps (Figure 1).

Table 1 Comparison of sulphate and bicarbonate ion concentrations between different glaciers. All values are in μeq l^{-1}, with the mean in brackets and the range giving the maximum and minimum values recorded. * represents studies cited in Brown (2002).

Glacier	Source	Non-snowpack SO_4^{2-}	HCO_3^-
Miage Glacier, Italy in 2010 (all proglacial samples)	This study.	**(202) 97-473**	**(777) 344-1186**
Miage Glacier, Italy in 2011 (all proglacial samples)	This study.	**(215) 128-323**	**(603) 494-688**
Haut Glacier d'Arolla, Switzerland	Brown et al. (1996)*	30-240	180-460
Austre Brøggerbreen, Svalbard	Tranter et al. (1996)	10-140	145-520
Scott Turnbreen, Svalbard	Hodgkins et al. (1998)	(130) 96-200	(170) 110-260
Scott Turnbreen, Svalbard (icing)	Hodgkins et al. (1998)	(830) 0-3200	(1800) 350-4600
Dokriani Glacier, India (pre monsoon)	Hasnain and Thayyen (1999a)	160-418	159-397
Dokriani Glacier, India (monsoon)	Hasnain and Thayyen (1999a)	85-1140	128-1053
Dokriani Glacier, India (post monsoon)	Hasnain and Thayyen (1999a)	137-431	168-384
Nigardsbreen, Norway	Brown (2002)	7-40	1.4-8.5
Tsanfleuron, Switzerland	Fairchild et al. (1994)*	118	627
Fjallsjökull, Iceland	Raiswell and Thomas (1984)*	26-66	190-300
Chamberlain, USA	Rainwater and Guy (1961)*	29-310	150-200
Engabreen, Norway	Ruffles (1999)*	0-142	51-675
Grimsvötn, Iceland	Steinpórsson and Óskarsson (1983)*	132	573
Batura Glacier, Pakistan	Hodson et al. (2002)	160	730
Bench Glacier, Alaska	Anderson et al. (2000)*	262	427
Gangotri Glacier, India	Kumar et al. (2009)	(673) 333-1186	(1138) 17-4130

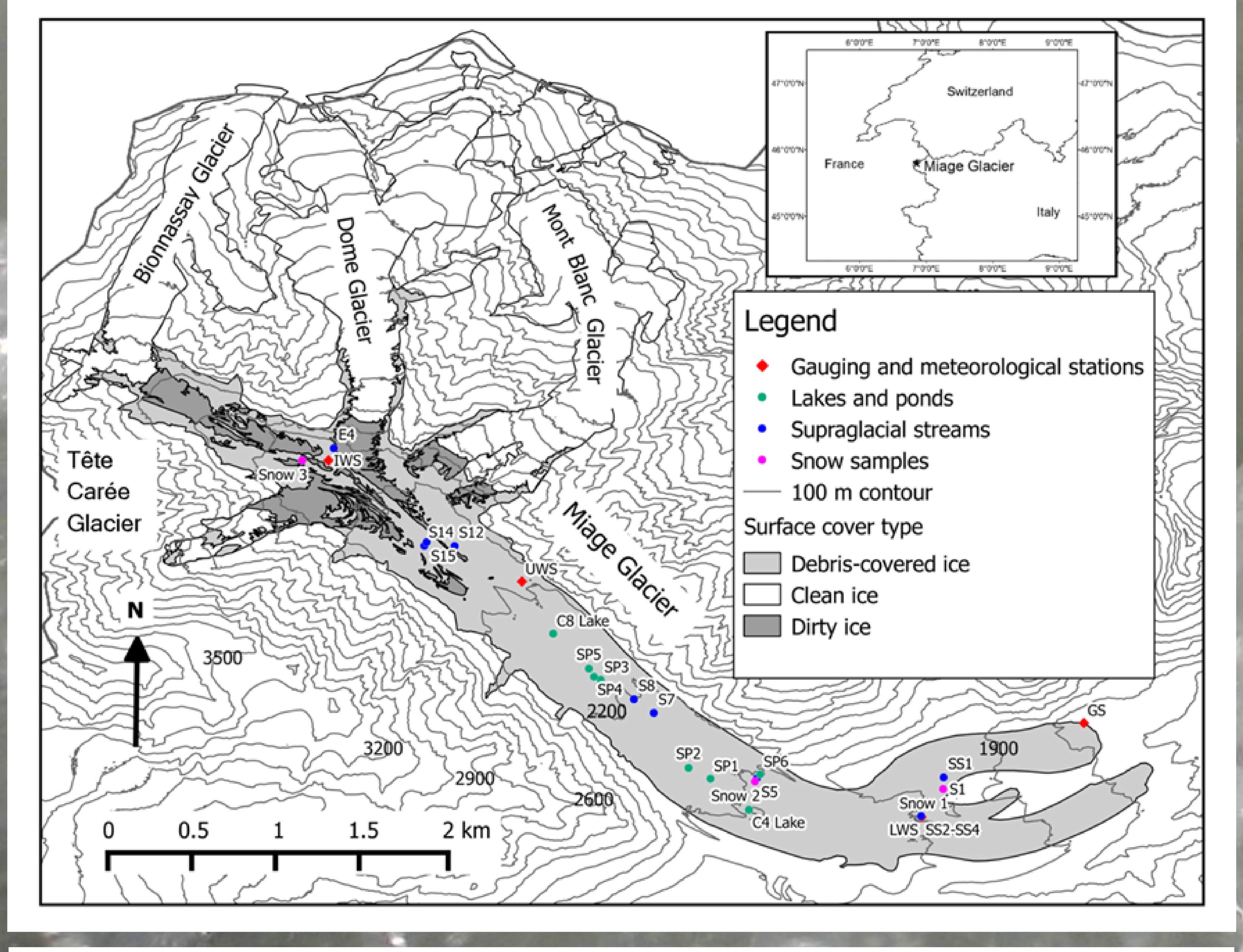


Figure 1 Miage Glacier showing the location of water chemistry samples and gauging and meteorological stations.

2. Water chemistry

The debris cover on the lower glacier increased the supraglacial suspended sediment and bicarbonate concentrations, and where residence times were long, sulphate concentrations. Proglacial bicarbonate and sulphate concentrations were high compared to those for clean glaciers (Table 1). Although a proportion of the ions have a supraglacial origin, the less efficient drainage network beneath the debris-covered tongue is thought to be the predominant cause.

3. Proglacial runoff

Compared to published data for clean glaciers, fewer diurnally classified daily hydrographs were found in the proglacial discharge record (Table 2), with the amplitude of the diurnal signal peaking later and being relatively low in amplitude. These hydrograph characteristics were due to the debris' attenuation of the melt signal, smaller input streams and less efficient subglacial drainage system beneath the debris-covered lower tongue. Warmer than average weather conditions were required for strongly diurnal hydrographs to be shown (Figure 2a and b), with a 'saw-toothed' hydrograph shown under average conditions (Figure 2c and d).

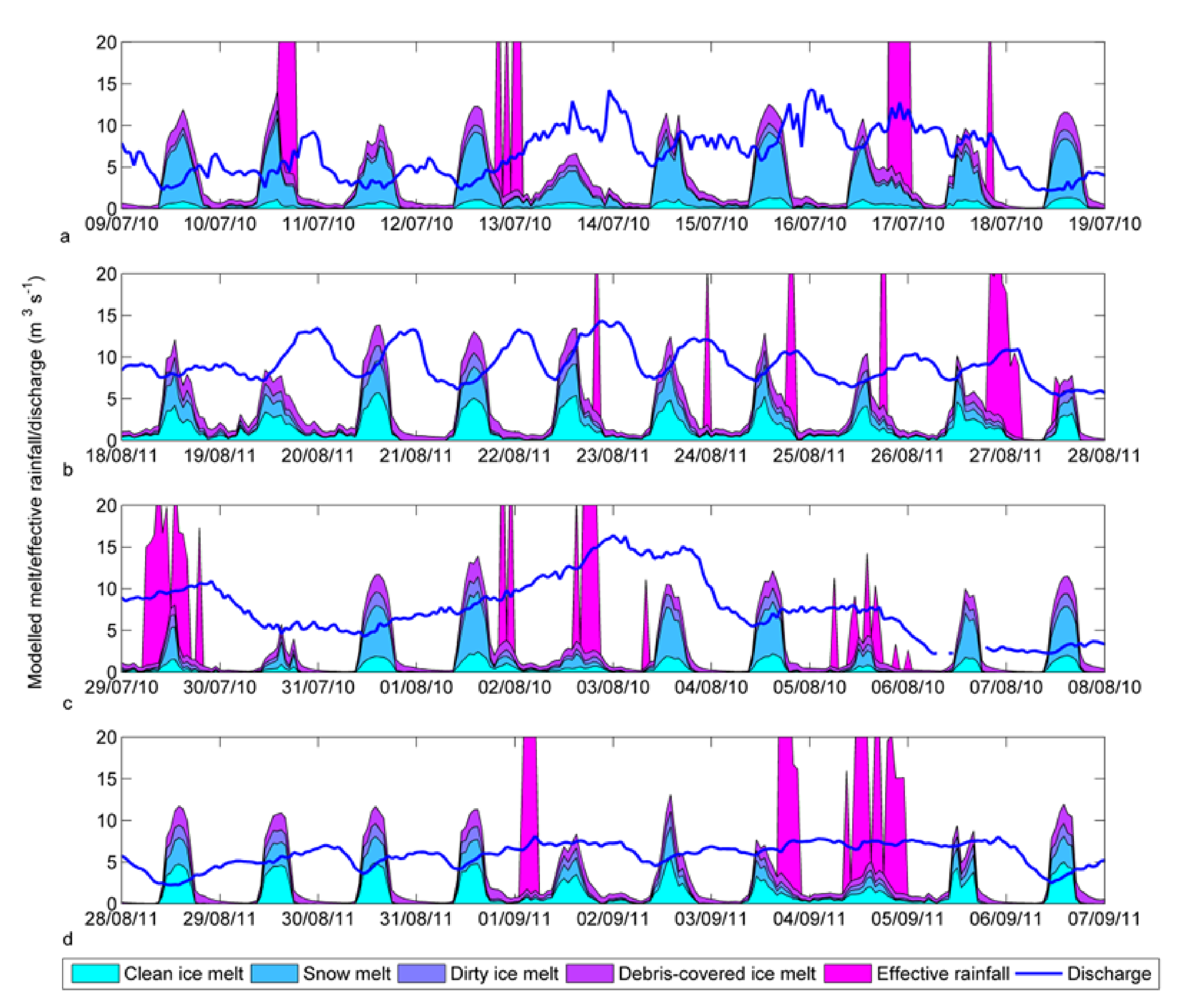
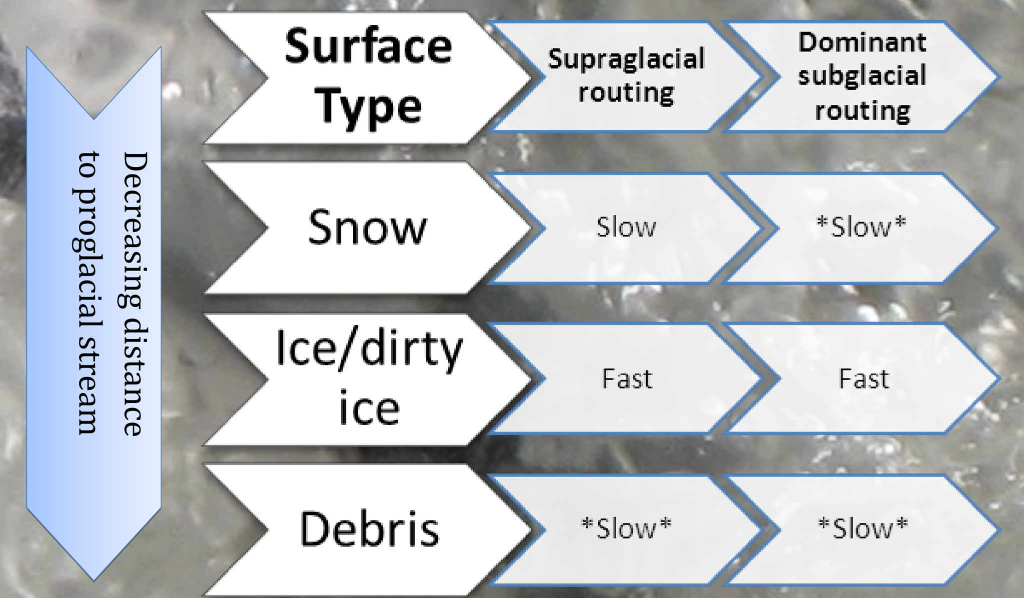
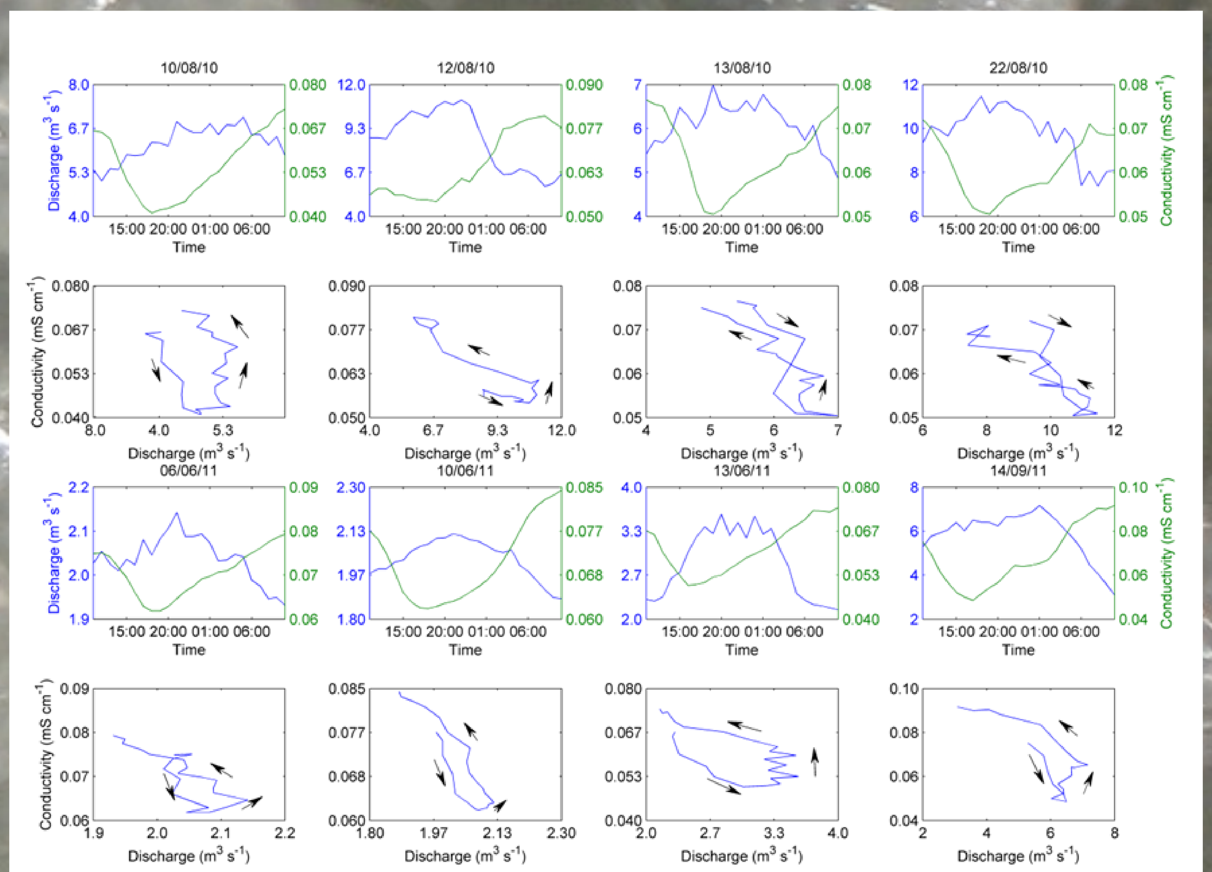


Figure 2 Close up of proglacial discharge and modelled melt and effective rainfall for each of the different surface types (shown as an area plot) for a) Phase 2 in 2010, b) Phase 2 in 2011, c) Phase 3 in 2010 and d) Phase 3b in 2011. Note that the y-axis has been constrained to 20 m^3 s^{-1} to allow discharge fluctuations to be seen more clearly.

Table 2 Table of hydrograph classification statistics for selected glaciers, with 'N' the number of hydrographs and '%' the percentage of total.

Hydrograph classification	Miage Glacier				Haut Glacier d'Arolla (Swift et al., 2005)				Taillon Glacier (Hannah et al., 1999)	
Year	2010		2011		1998		1999		1995+1996	
	N	%	N	%	N	%	N	%	N	%
Rising (*Building/Late Peaked for Taillon)	26	36	20	38	21	13	30	19	41*	35*
Falling	15	21	7	13	27	17	28	18	12	10
Peaked Falling (Arolla only)					11	7	5	3		
Peaked/Diurnal	32	44	25	48	97	62	91	59	56	48
Attenuated (Taillon only)									8	7





Above: Figure 3 Conceptual diagram of runoff components, and their relative travel time class for a debris-covered glacier. The stars indicate where solute could be acquired by the meltwater.
Right: Figure 4 Plots of hourly discharge and conductivity data for days with diurnally classified discharge and conductivity in 2010 (rows 1 and 2) and 2011 (rows 3 and 4). Note the day starts at 11:00. The temporal relationship between hourly discharge and conductivity is given below the time series plots.

5. Conclusions

The overall influence of the debris is to increase the suspended sediment and ion concentration of the proglacial stream. The proglacial runoff signal is also more subdued with a longer lag to peak and fewer clearly diurnal hydrographs.

4. A model of water routing for a debris-covered glacier

Since the debris attenuates the input melt signal and results in a less efficient subglacial system this means the flow component composed of sub-debris melt has a longer lag time than the flow component from the clean and dirty ice which is routed efficiently from the mid-glacier (Figure 3), thus increasing the baseflow component of discharge. Discharge and conductivity commonly showed anti-clockwise hysteresis with conductivity and discharge often rising in phase for a few hours (Figure 4). This suggests that the dilute melt component from the mid-glacier ('ice/dirty ice' in Figure 3) likely peaks before the more ion rich 'debris' and 'snow' components.