Hydrograph and chemograph separation of bulk meltwaters draining the upper Arolla Glacier, Valais, Switzerland

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ABSTRACT A new method of the hydrograph separation of bulk meltwaters into englacial and subglacial components is examined. Diurnal bulk meltwater discharge, conductivity and calcium cycles in June and July demonstrate that the composition of the subglacial component is not constant, and is dissimilar to the season's highest recorded conductivity or calcium concentration.

INTRODUCTION

The separation of the hydrograph of Alpine glacial meltwaters into even two components is problematical, because of the dynamic nature of the hydroglacial system. There are likely to be seasonal variations in the distribution and efficiency of the drainage network and the seasonal variation in discharge is well documented (Rothlisberger and Lang, 1987). These factors affect the residence time of water within the hydroglacial system, and hence the chemical composition of the various components of bulk meltwater discharge are likely to vary throughout the season (Tranter and Raiswell, in prep). Collins (1978, 1979) suggested that the composition of bulk meltwaters can be explained by the mixing of two components. The first, the subglacial component, is concentrated and dominates bulk discharge at low flow, while the second, the englacial component, is dilute and dominates bulk discharge at high flow. Collins (1978, 1979) adopted a pragmatic approach to hydrograph separation based on conductivity determinations. He suggested that the composition of both components is constant, corresponding to the season's highest and lowest bulk meltwater values. In this paper, we compare this pragmatic approach with the results of a new method of hydrograph separation (Tranter and Raiswell, in prep).

STUDY AREA

Haut Glacier d'Arolla is located in the Val d'Herens, Valais, Switzerland (Fig.1.). The Haut Arolla basin comprises an area of 11.74 km² of which 6.33 km² (54%) is glacierized. A compound firn basin (max. elevation 3838 m) feeds the main ice tongue which terminates at 2560 m. The tributary Glacier de la Mitre joins the main ice tongue in
FIG. 1 The Haut Arolla catchment.
the west, though the compound Glacier de Bouquetins remains distinct and supplies meltwater and sediment only to the Haut Arolla system. Despite recent periods of advance by other glaciers in the area (eg. Tsidjiore Nouve and Bas Arolla), Haut Arolla has shown a marked contraction (520 m 1967 - 1977, 200 m 1977 - 1989). The catchment is underlain by schist and gneiss of the Arolla series. It forms part of the Grande Dixence, S.A. hydroelectric power scheme. Extraction of water is effected 950 m from the snout, downstream from the sampling site, which is located some 100 m from the snout.

METHODS

Sampling was undertaken hourly between consecutive minimum flow conditions, during two 24h periods in June and July. Samples were also collected near to minimum and maximum discharge on most days throughout the field season. Bulk meltwaters were filtered immediately through a 0.45 μm membrane, under vacuum, in a pre-washed apparatus and decanted into clean 60 ml plastic bottles. Samples for Ca\(^{2+}\) analysis were acidified with 1 ml of Analar HNO\(_3\) in the field. Discharge data was obtained from Grande Dixence measurements taken at an intake structure approximately 1 km from the snout. The accuracy of the data is ± 4%. Conductivity values were continuously recorded at the sampling site using a pHOX 57 (Mk.2) meter with a resin carbon electrode probe (cell constant 1.0). Accuracy is ± 3%. Temperature compensation was not employed. The temperature of the bulk meltwaters was 0.7 ± 0.7 °C throughout the sampling season. Hence, since temperature correction is approximately 2% per degree, an error of ± 5% is associated with the measurements. Calcium concentrations were determined on a Pye-Unicam flame spectrometer (model SP9) with an air-acetylene flame. Accuracy was ± 5%, as determined by standard additions. Precision was also ± 5%.

RESULTS

The 24h cycles discussed here fit into a run of hydrochemical data that cover virtually the whole of the 1989 melt season for the Haut Arolla catchment. Seasonal traces for discharge, conductivity (representing total dissolved solids) and calcium (the major cation) are shown in Fig.2. Low early season discharge levels soon develop into a regular diurnal cycle showing the characteristic inverse relationship between discharge and solute concentration. The maximum amplitude of all three variables occurs in July which is characterised by a long period of uninterrupted diurnal cycles. Major disruptions to the pattern occur at 23/6, 02/7, and 30/8 when snowfall covered the glacier. The two diurnal cycles examined here are from 22nd - 23rd June and 17th - 18th July.

Maximum conductivity values and calcium concentrations occur at the start of the season, when values of 38 μS/cm
FIG. 2 Variations in (a) discharge, (b) conductivity and (c) calcium concentration throughout the 1989 ablation season.
and 470 μeq/l were recorded. Minimum values occur during July, when values of 10 μS/cm and 165 μeq/l were recorded.

DISCUSSION

Figure 3 shows that for each of the diurnal cycles sampled during June and July, calcium and conductivity show strong linear associations with discharge, which explain between 89% to 97% of the variance. This linear association can be exploited to find the composition of the subglacial component. We follow the method of Tranter and Raiswell (in prep).

Let Qb be the bulk discharge, and let Qs and Qe be the contribution to the bulk discharge of the subglacial and englacial components respectively. Let C denote the conductivity or calcium concentration of the bulk meltwater (b), subglacial (s) and englacial (e) component. Conservative mixing of the englacial and subglacial components requires that

\[ \frac{Q_e}{Q_b} = \frac{(C_s - C_b)}{(C_s - C_e)} \]  

(1)

Since there is a linear association between Cb and Qb,

\[ C_b = mQ_b + k \]  

(2)

where m and k are constants.

Substituting equation 2 into equation 1 and rearranging gives

\[ \frac{Q_e}{Q_b} = \frac{-mQ_b + C_s - k}{(C_s - C_e)} \]  

(3)

We will assume that Cs and Ce are constants. Therefore, the bulk discharge, Qb, is a simple, linear measure of the mass fraction of the englacial component in the bulk meltwater, (Qe/Qb). The value of Cs is defined when the mass fraction of the englacial component is zero. Given this condition, from equation 3,

\[ Q_b = \frac{C_s - k}{m} \]  

(4)

Remembering that m is a negative value, Cs cannot be greater than k, since Qb cannot be a negative value. If Cs is less than k, this implies that at some value of Qb, let us say Qx, the discharge consists entirely of subglacial waters. At bulk discharge lower than Qx, the subglacial component must become more concentrated to satisfy equation 4. This
FIG. 3 Scatterplots of bulk meltwater conductivity or calcium and bulk meltwater discharge.
Regression equations:
a) \( C_b = -5.2 * Q_b + 27 \) \((R = -0.987, n = 24)\)  
b) \( C_b = -58 * Q_b + 310 \) \((R = -0.945, n = 24)\)  
c) \( C_b = -3.8 * Q_b + 32 \) \((R = -0.976, n = 23)\)  
d) \( C_b = -49 * Q_b + 390 \) \((R = -0.969, n = 23)\)
condition is not permissible given that we are assuming that the end-member compositions are constant. An alternative explanation is that if $C_s$ is less than $k$, there must be a constant discharge of subglacial water of fixed composition. In other words, a third component. This is also not permissible in a two component mixing model. Hence, $C_s$ must equal $k$.

Since $C_s = k$, the regression equations of $C_b$ against $Q_b$ define the composition of the subglacial component. Fig. 3a and 3b show that for the June diurnal cycle, the conductivity and calcium concentration of the subglacial component is 27 $\mu$S/cm and 310 $\mu$eq/l respectively, while for July, Fig. 3c and 3d show that the values are 32 $\mu$S/cm and 390 $\mu$eq/l. The conductivity and calcium concentration of the subglacial component are clearly not constant, and the values are dissimilar to the maximum recorded values for the season.

Methods to define a unique composition for the englacial component are presently being explored. The englacial component is likely to have a composition bounded by the composition of supraglacial meltwaters and the season's minimum bulk meltwater values for much of the ablation season. We have separated the hydrograph assuming that the composition of the englacial component is 1) that of more concentrated supraglacial meltwaters (conductivity = 2.7 $\mu$S/cm; calcium = 16 $\mu$eq/l) and 2) that of the season's minimum recorded bulk meltwater values (conductivity = 10 $\mu$S/cm; calcium = 165 $\mu$eq/l). Fig. 4a and 4b illustrate the range of errors associated with the englacial component being poorly defined. Clearly, greatest discrepancies occur when the bulk meltwaters are dilute and approach the composition of the englacial component. This is clearly illustrated in Fig. 4b, a hydrograph separation for the July diurnal cycle based on calcium concentrations. By assuming that the composition of the englacial component is that of supraglacial water, rather similar discharge of each of the components at maximum bulk discharge is produced. By assuming that the englacial component has the season's lowest recorded calcium concentration of the bulk meltwaters, a much different separation is produced. In this case, the subglacial component is cut off at maximum discharge.

Hydrograph separations based on conductivity and calcium produce broadly similar patterns of hydrograph separation. However, the ratio of the values calculated or chosen for each of the components differs. Hence, the exact values for the discharge of each component varies. The best agreement between the calcium and conductivity based separation is for June, assuming that the composition of the englacial component is approximated by the composition of supraglacial waters. Regression analysis of $Q_e$ determined by calcium and conductivity values gives a slope of 1.06 and an intercept of 0.01. The correlation coefficient is 0.990. Perfect agreement between the different methods of hydrograph separation would produce a slope of 1.00 and an intercept of
FIG. 4 Hydrograph separation of bulk meltwater discharge. Subscripts 1 and 2 denote the assumptions made in determining the composition of the englacial component (see text).  
(a) The June hydrograph, separated by conductivity values.  
(b) The July hydrograph, separated by calcium concentrations.
CONCLUSIONS

The composition of subglacial waters may vary throughout the melt season. Their composition is therefore not best represented by the season's highest recorded values in bulk meltwaters. The composition of the englacial component must be determined accurately if the hydrograph separation of dilute bulk meltwaters is to be determined with confidence.

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