Seasonal variations of water temperature and discharge in rivers draining ice-free and partially-glacierized Alpine basins

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ABSTRACT
Records of discharge and temperature of water in rivers draining from 3 Alpine basins between ice-free and 66% glacier-covered, in the upper Aare and Rhône catchments, Switzerland, were examined in order to assess the impacts of percentage glacierisation of large basins on runoff regime and seasonal pattern of river water temperature. The month with maximum runoff is delayed from May for the ice-free Allenbach to July and August for the ice-melt dominated Lonza and Massa. Ice-melt contributions to runoff suppressed water temperatures in summer in the two glacier-fed rivers, but a distinctive seasonal temperature regime was observed only in the Massa, draining the most highly-glacierised basin. Maximum water temperature in the Massa occurred at low flow in April. Subsequently as icemelt discharge increased, water temperature decreased and mean monthly temperature was maintained at about the same level between July and September.

KEYWORDS
alpine basins, glacierized basins, glacier-fed rivers, water temperatures

1. INTRODUCTION
Orographically-enhanced levels of precipitation lead to contributions of high specific discharges from headwater mountain basins to the great continental rivers. Such large fluxes of water are increased in glacierised high mountain basins, as glaciers generally decline in mass and reduce in size from dimensions attained during the Little Ice Age (*e.g.* Maisch & others 1999; Collins 2008). During a period of glacier decline, net melting of ice from storage adds a component of flow to runoff from glacierised Alpine basins in excess of that related to contemporary levels of precipitation. This additional component of flow can not be sustained indefinitely, for, should the climatic trend continue, glaciers will ultimately disappear, and runoff be reduced to levels solely reflecting precipitation.

Total runoff in a year from ice-free Alpine basins is always less than the annual total precipitation, is directly proportional to the amount of precipitation and has a spring maximum during the period of melt of stable seasonal snowpack. In glacierised Alpine basins, a component derived from the glacier itself is added to the fraction of runoff arising from the ice-free area of the basin. Total annual runoff from the glacierised area essentially depends on the interaction between snowfall and the amount of heat energy available for melt, and can be more than, equal to, or less than the level of precipitation, with the seasonal maximum occurring in July or August. The sooner and higher the transient snowline rises in early summer, the thicker the layer of ice melted as a larger area of ice is exposed to melt for longer. High runoff from a glacier, therefore, is favoured in years in which warm summers follow winters with limited snow cover, years in which runoff from the ice-free area is relatively low, the actual effect on basin runoff being influenced by the relative areal dimensions of the ice-free and glacier-covered portions of a catchment (*e.g.* Collins 2008).

Such distinctive regimes of snow- and ice-melt dominated runoff might be expected to lead to similarly distinctive seasonal patterns of variability of Alpine river water temperatures. Water temperature is an important variable in hydrochemistry and hydroecology, and impacts of changing large contributions of cool icemelt-derived water as glaciers decline are likely not only to have headwater effects but also to influence thermal characteristics of rivers for some distance downstream (*e.g.* Webb & Nobilis 1995). Alpine rivers are fed by liquid precipitation as well as snow- and ice-melt in warmer months, and by groundwater throughout the year. Each water source has a characteristic thermal signal, which is then modified during downstream flow according to heat capacity by interaction with ambient environmental thermal energy availability. Thermal regimes of alpine rivers have received considerable attention (*e.g.* Uehlinger & others 2003; Brown & others 2006), but where glacierised basins have been investigated, glacier areal dimensions and/or proportions of basins glacierised have been small. For example, in a study of stream temperature dynamics in the Southern Alps of New Zealand by Cadbury & others (2008), Rob Roy Glacier occupied 4.8 km^2 of the small eponymous basin of 16 km^2.

The aim of this paper is to examine the influence of percentage glacierisation on flow regime and seasonal patterns of water temperature variation in proglacial rivers draining from large glacierised basins (75 – 195 km^2 with 36 – 76 % glacierisation respectively) in the Berner Oberland and Pennine Alps, Switzerland. Significant ice-melt proportions of high specific discharges from large basins, with high heat capacities, might be expected in summer to extend cooling thermal influences considerable distances downstream.

2. STUDY BASINS AND MEASUREMENTS

The Lonza and Massa, two partially-glacierised sub-basins of the upper Rhône catchment, in Kanton Wallis, Switzerland, were selected for study, together with the Allenbach, an ice-free sub-basin of the contiguous upper Aare, in Kanton Bern. Dimensions of the selected basins, to the gauging stations at Blatten, Blatten-bei-Naters and Adelboden respectively, together with percentage glacierisation and mean annual runoff are given in Table 1.

Table 1 Characteristics of basins: area, glacierised areas (2002) and runoff (1956-2005)

RIVER/GAUGING STATION	BASIN AREA (KM^2)	BASIN GLACIERISATION (%)	MEAN RUNOFF (M)
Allenbach/Adelboden	28.8	0.0	1.312
Lonza/Blatten	77.8	36.5	1.905
Massa/Blatten-bei-Naters	195.0	65.9	2.112

Basin locations are shown in Figure 1, and elevation ranges and vertical extents of glacierised areas and basins are shown in Figure 2. The three basins are exposed to the same overall pattern of climatic influences, although precipitation in Alpine areas is far from uniformly distributed. Elevations of the gauging stations are in a band of a few hundred meters.

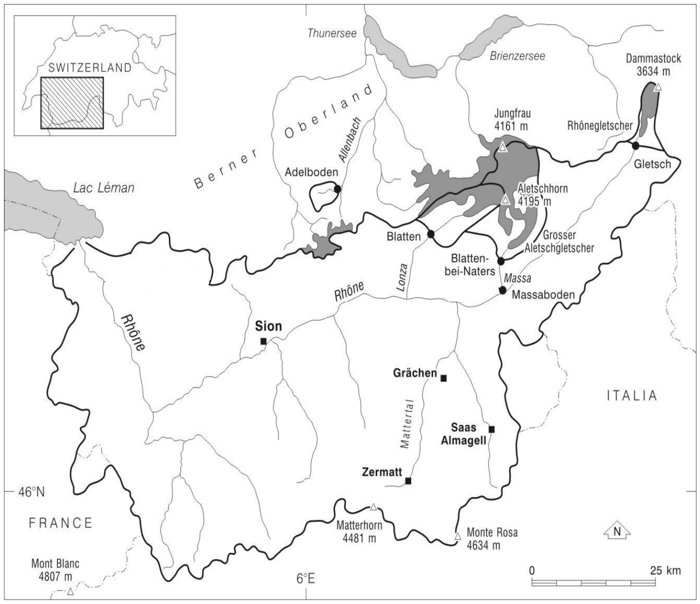

Figure 1 Locations of the three study basins in the upper Aare and Rohne basins, Switzerland. Glacierised areas within the study basins are shaded.

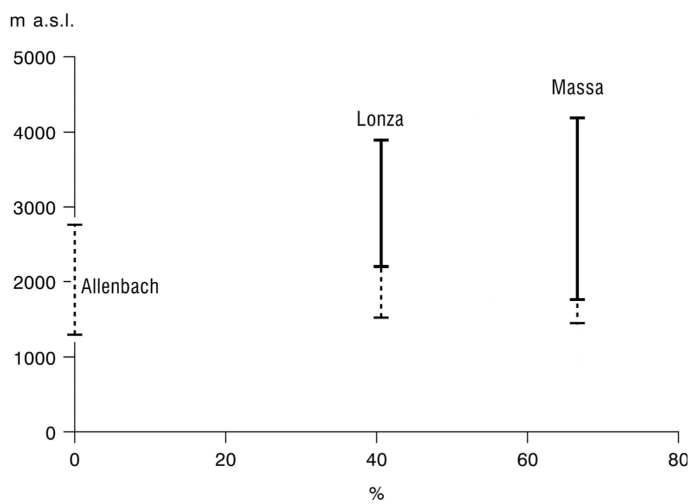

Figure 2 Elevations of upper and lower limits of glacierised areas (solid lines) and basins (broken lines) plotted against percentage basin glacierisation.

Water temperature was recorded at the three stations with hourly resolution throughout the calendar years of 2003 through 2007 by Bundesamt für Umwelt (BAFU). Discharge has been recorded for more than 55 years at all three stations by BAFU (*e.g*. Bundesamt für Wasser & Geologie 2003).

3. BASIN CHARACTERISTICS AND RUNOFF REGIME

Both glacierisation and mean annual runoff in Alpine basins might be expected to increase with catchment elevation, and such is confirmed by the three study basins. Whilst glacierised area increases with elevation of upper basin limit (Table 1, Figure 2), percentage glacierisation is influenced also by distance downstream from glacier terminus to gauging station location. Also, the longer the distance between glacier terminus and gauge, the more opportunity there will be for meltwater to be warmed by direct radiation.

For the ice-free Allenbach basin, maximum mean monthly runoff occurs in May, with on average 52.5 of total annual runoff occurring during snowmelt in the four months April through July (Fig.3). As basin glacierisation and basin elevation increase, maximum mean monthly runoff is delayed to July in the Lonza and to August in the Massa, with averages of 85.1 and 92.3%, respectively, of total annual runoff occurring in the five summer months May through September. Including October as a sixth summer month, these percentages of total runoff in the ablation season become 90.7 and 97.1, emphasising how meltwater dominates runoff once glacier ice covers a substantive portion of a basin. Such delays between precipitation and runoff are classic features of the distinctive nature of glacier runoff (Meier & Tangborn 1961).

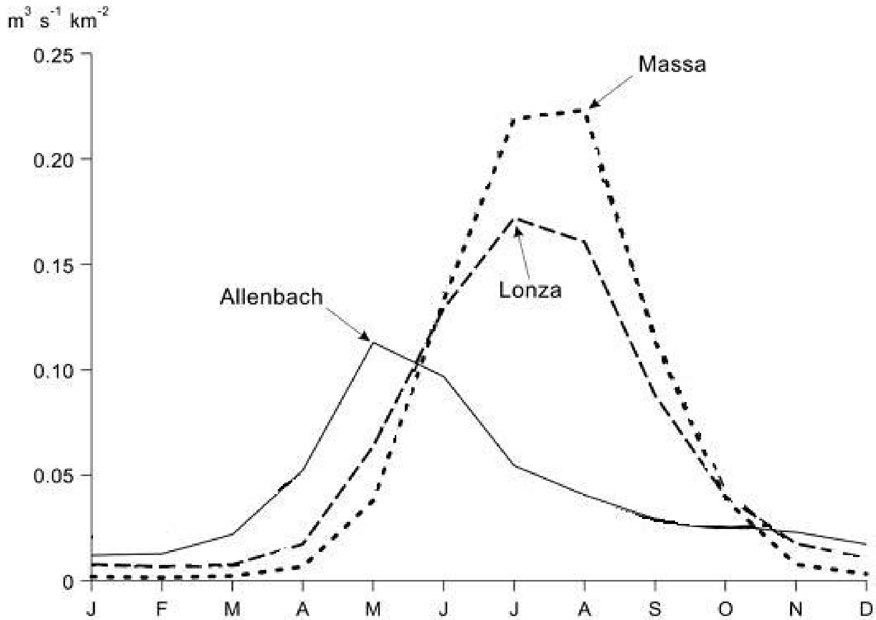

Figure 3 Mean monthly specific discharge in the Allenback, Lonza and Massa rivers for the period 1956-2007

4. RIVER WATER THERMAL REGIME

Figure 4 shows mean monthly water temperatures at the three stations averaged for the five-year period 2003-2007. Mean monthly water temperature in the Allenbach in winter remains below

2°C between December and February, runoff arising from groundwater and limited snow melt. As snowmelt increases flow from March to May, water temperature warms alongside rising radiation. Increasing snowmelt runoff provides a greater volume of water to heat (a mean monthly discharge of 3.08 m^3 s^{-1} in May), restraining the rise in water temperature. The rate of increase in water temperature is then enhanced as snowmelt wanes in June, reaching a maximum monthly mean of 10.2 °C in July. Subsequently water temperature in the Allenbach follows the decline in radiation along with discharge. There is no glacial influence in the Allenbach, which illustrates the nival Alpine runoff – water temperature regime.

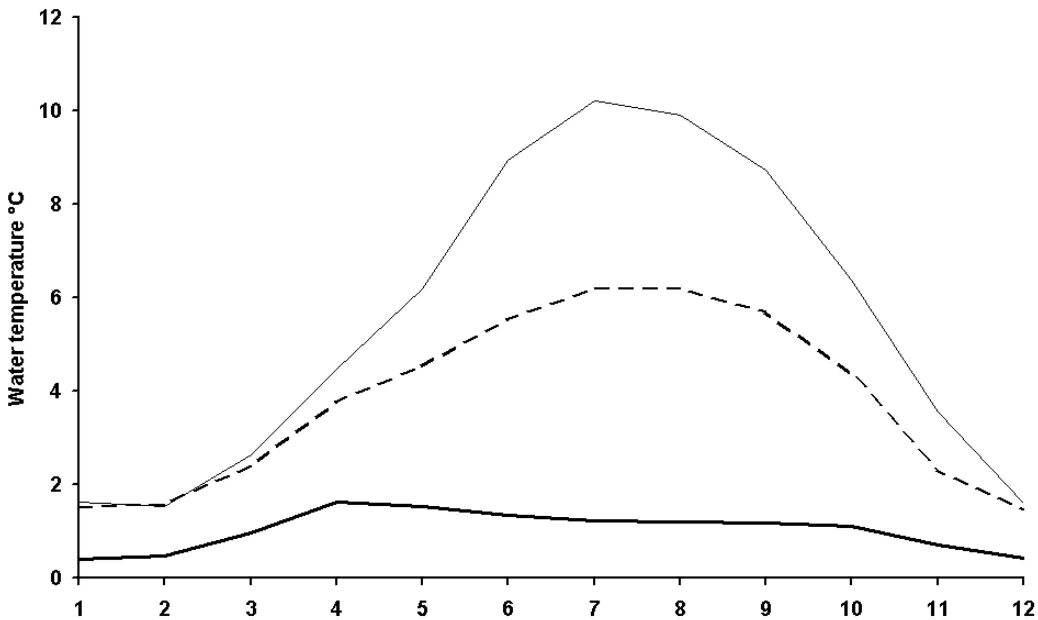

Figure 4 Averages for the period 2003-2007 of mean monthly water temperatures in the Allenbach, Lonza and Massa rivers from January (1) through December (12).

At the other end of the spectrum, the Massa drains a large highly-glacierised basin. Flow first starts to increase only in May to a mean monthly flow of about 11 -12 m^3 s^{-1}, before steeply rising to a maximum in July or August (mean monthly flow of between 50 and 60 m^3 s^{-1}). Initially, increasing radiation in spring is able to raise the temperature of water in the Massa to a maximum mean monthly level of ~1.6 °C in April (much below the equivalent 4.5 °C for the Allenbach). In face of rising radiation, increasing discharge of water derived from icemelt that has passed through the internal drainage system of Grosser Aletschgletscher, leaving the portal with a temperature of <1.0 °C, starts to reduce water temperature in the Massa in May (~1.5°C). Continuing increase in volume of flow, raising the heat capacity of the Massa, offsets maximum radiation in June and July and meltwater gains little heat in the short distance between glacier portal and gauge, mean monthly temperatures falling to 1.2 °C in July and August. By September and October, falling radiation is offset by greatly reduced discharge (about 26 and 9 m^3 s^{-1} mean monthly flows respectively) to maintain temperature of meltwater at a monthly average of about to 1.2 °C before falling back to winter mean levels of 0.4 °C.

For the Lonza, the basin of which is 36.5 per cent glacierised above Blatten, the gauge is located at a distance of ~7 km from the terminus of Langgletscher, allowing meltwater leaving the glacier at less than 1.0 °C to be warmed by the time the gauge is reached. As indicated in Fig. 4, the seasonal variation of temperature of water in the glacierised Lonza more reflects that of water in the ice-free Allenbach. Mean monthly water temperature in the Lonza exceeds 5.5 °C between June and September in spite of mean monthly discharges of ~12 m^3 s^{-1}. Nonetheless, water temperatures in the Lonza remain on the average about 3 Celsius degrees below those in the Allenbach.

5. DISCUSSION AND CONCLUSION

Storage of ice clearly modifies flow regime where glaciers exist in Alpine basins by delaying runoff to the summer months. Whilst water temperature is generally reduced as the proportion of snow- and ice-melt in the total runoff that has passed through the internal drainage system of the glacier increases, the effect is most apparent in the Massa. Volumetric flow is large, raising the heat capacity of the river, and the time during which heating can occur is limited by the short distance between glacier portal and gauge. For a parcel of water flowing from the glacier, transit time is further reduced in summer as velocity increases with discharge. These factors offset the high levels of energy availability, principally radiation, for both melting of ice in summer, and warming river water. The pattern of spring warming followed by summer cooling in the Massa reflects the volume of flow. In spring, with relatively low discharge and extended transit times, the small quantities of river water warm up in the increasing levels of radiation. In summer, the mass of ice-melt derived water emerging at < 1.0 °C requires more energy to raise the temperature of the river, but there is reduced transit time in which for energy exchange can take place. Relationships between energy availability, glacier ice melt, discharge and water temperature in a river draining from an Alpine glacierised basin are shown schematically in Figure 5. Although water temperature is directly influenced by energy availability, increased icemelt leading to increased discharge also enlarges the volume of water exposed to heating alongside reducing the transit time from the glacier portal as velocity increases. These negative links lead to lower water temperatures even at times of high energy availability.

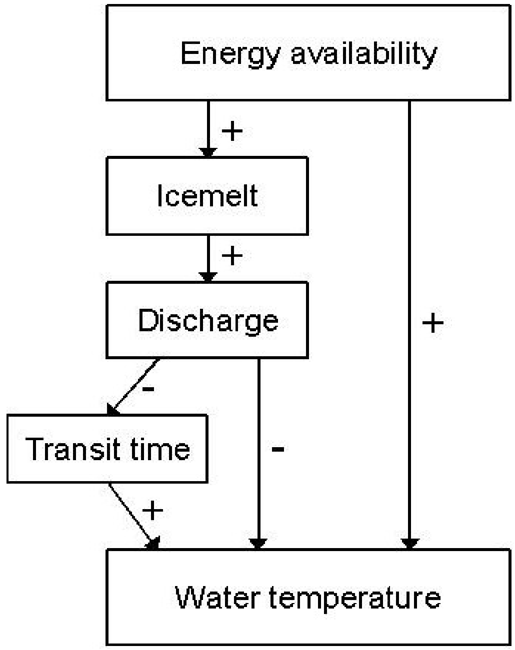

Figure 5 Schematic diagram showing the relationships between energy availability, glacier ice melt, discharge and water temperature in a river draining from an Alpine glacierised basin.

In the Lonza, discharge and hence mass of ice-melt derived water warming on flowing away from the portal is considerably less than in the Massa. The longer the distance from portal to gauge, the greater the transit time and exposure to radiation. Although water in the Lonza remains cooler than in the Allenbach, the distinctive seasonal pattern of water temperature variation in the Massa is absent. The suggestion must be that a distinctive river water temperature regime exists only in larger rivers and close to portals of the large glaciers from which such rivers drain.

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