Climatic variation and runoff in mountain basins with differing proportions of glacier cover*

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Abstract Records of discharge from partially-glacierised basins in the upper Rhône catchment, Switzerland, were examined together with air temperature and precipitation data in order to assess impacts of climatic fluctuation and percentage glacierisation of basin on runoff, as glaciers declined from dimensions attained during the Little Ice Age. Above 60% glacierisation, year-to-year variations in runoff mimicked mean May–September air temperature, rising in the warm 1940s, declining in the cool 1970s, before increasing (by 50%) into the warm dry 1990s/2000s but not reaching 1940s maxima. In basins with between 35–60% glacierisation, flow also increased into the 1980s but waned through the 1990s. With less than 2% glacierisation, the pattern of runoff was broadly the inverse of that of temperature and followed precipitation, dipping in the 1940s, rising in the cool wet late 1960s, and declining into the 1990s/2000s, with glacier melt in warm years being insufficient to offset lack of precipitation. On mid-sized glaciers at relatively low elevations and with limited vertical extent, in warmer years, the transient snow line was above the highest point of the glacier. Only on large glaciers descending from high elevations can rising transient snowlines continue to expose more ice to melt. Runoff from such large glaciers was enhanced in warm summers but reduction of overall ice area through glacier recession led to runoff in the warmest summer (2003) being lower than the previous peak discharge recorded in the second warmest year (1947).

Keywords Climatic fluctuation; glacierised basins; glacier recession; meltwater discharge; runoff

Introduction

As glaciers decline from dimensions attained during the Little Ice Age, destocking of ice adds a component to runoff from glacierised Alpine basins in excess of that related to contemporary levels of precipitation. This additional component of flow can, however, not be sustained indefinitely as, if climatic trends continue, glaciers will ultimately disappear, and runoff will be reduced to amounts solely reflecting levels of precipitation. Runoff from a glacierised basin consists of two fractions, one arising from the ice-free portion of the basin and the other from the glacier itself. Opposing hydrological responses in the ice-free and glacier-covered portions of a catchment to the same hydrometeorological input tend to moderate year-to-year variation of runoff from a glacierised basin (e.g. Tvede 1982). Hence, even a small percentage of ice cover ($<1\%$) reduces the variability of annual total runoff with respect to that of annual total precipitation (Kasser 1959), variability declining further to a minimum as glacierisation extends to between 20–60% of basin area (Krimmel and Tangborn 1974; Fountain and Tangborn 1985; Collins 1988). That this interaction is influenced by the relative areal dimensions of ice-free and glacier-covered portions of a basin (as well as by precipitation and thermal energy availability for melting) suggests that

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percentage glacierisation of basin will affect runoff responses to warming climate and associated declining glacier cover.

How runoff responds to declining glacierisation will also depend on the rate at which energy input is enhanced through time, any changes in precipitation regime, and on the scale and rapidity of change in glacier planimetric dimensions coupled to those climatic fluctuations. The aim of this paper is to describe variations in hydrometeorological conditions and runoff from Alpine glacierised basins with differing percentage glacier cover, during a period of climatic fluctuation coupled with sustained glacier decline. Four basins in the upper Rhône catchment, above Lac Leman, Switzerland, previously studied by Collins (1989a), are examined.

Total runoff in a year from the ice-free zone is always less than the annual total precipitation over that area, is directly proportional to the amount of precipitation, and has year-to-year variability close to that of precipitation. Total annual runoff from the glacierised area essentially depends on the interaction between snowfall and the amount of heat energy available for melt. The sooner and higher the transient snowline rises in early summer, the thicker the layer of ice melted and the larger the area of ice exposed to melt. High runoff is favoured therefore when warm summers follow winters with limited snow cover. Under such conditions, runoff can exceed precipitation as the glacier loses more mass through ice ablation than is replenished by snow accumulation above the final high elevation to which the transient snow line rises. Conversely, in cool summers preceded by winters with considerable snow accumulation, runoff will be depleted. Collins (1989a) considered that amounts of runoff from Alpine glacierised basins would probably be maintained for some time during a period of sustained warming even though glaciers continued to retreat. In warm summers, the transient snowline would rise to higher elevations, expanding the area of bare ice exposed to melting, and offsetting the loss of planimetric area at lower ice margins. This would continue until such time that the transient snowline had risen above the upper limit of the glacier at high elevation. Addition of 15 years' data to the hydrometeorological and discharge records available in the late 1980s now allows evaluation of this prognostication. Although runoff from basins containing declining glaciers will, in the end, be reduced, there remains also the question of whether flow might first increase before decreasing, as has been suggested in some commentaries (e.g. Jansson *et al.* 2003; Pearce 1999; World Wildlife Fund 2005).

Study area

The same partially-glacierised Alpine basins in the upper Rhône catchment, above Lac Leman, Valais/Wallis, Switzerland, as previously studied by Collins (1989a), were selected for study. Records of runoff for periods of almost 50 years or more are available from the gauging stations defining four sub-basins of the Rhône. With the exception of the Grande Eau basin, which is slightly influenced by water storage, the catchments are subject only to natural flow. The four basins have differing extents of glacier cover but are all exposed to the same pattern of climatic influences. Physiographic characteristics of the basins and glaciers are given in Table 1, and locations shown in Figure 1.

Overall glacier-covered area as a percentage of total basin area has been taken from the contemporary annual *Hydrologisches Jahrbuch der Schweiz* (e.g. Bundesamt für Wasser und Geologie 2003 *et seq.*). The steep eastern rim of the Grande Eau basin is fringed by very small discontinuous glaciers, such as Glacier de Pierredar (1.25 km^2 in 1973), which were slightly reduced in size in the last quarter of the twentieth century. Total glacier-covered areas of about 32 and 22 km^2 in the Lonza and Rhône basins declined by about 10% and 7.5%, respectively, during the same period. Following construction of a dam, the gauge on

Table 1 Characteristics of glacierised areas and drainage basins

River/gauging station	Basin area (km^2)	Basin elevation range (m a.s.l.)	Principal glacier	Basin glacierisation (year)	Basin glacierisation (%)	All glacier elevation range (year)	All glacier elevation range (m a.s.l.)
Grande Eau/Aigle	132.0	414–3210	Glacier de Pierredar	1977	1.9		
				2002	1.8	2000	2450–3005
Lonza/Blatten	77.8	1520–3897	Langgletscher	1977	40.6		
				2002	36.5	2004	2200–3892
Rhône/Gletsch	38.9	1761–3634	Rhônegletscher	1977	56.4		
				2002	52.2		2200–3630
Massa/Massaboden	202.0	687–4195	Grosser Aletschgletscher	1934	67.6		
				1957	64.1		
Massa/Blatten-bei-Naters	195.0	1446–4195		1934	70.0		
				1957	66.4		
				1977	66.6		1760–4193
				2002	65.9		

the Massa was relocated to Blatten-bei-Naters, upstream of the former station at Massaboden, from 1965, with a concomitant reduction in basin area of 3.47%. Percentage glacierisation of the Massa, recalculated to take into account that change in catchment area in Table 1, reflects a reduction in total ice-covered area of about 8 km^2 (6%) by 2002, from 136.6 km^2 in 1934. Of this total areal loss, about three-quarters had disappeared by 1957.

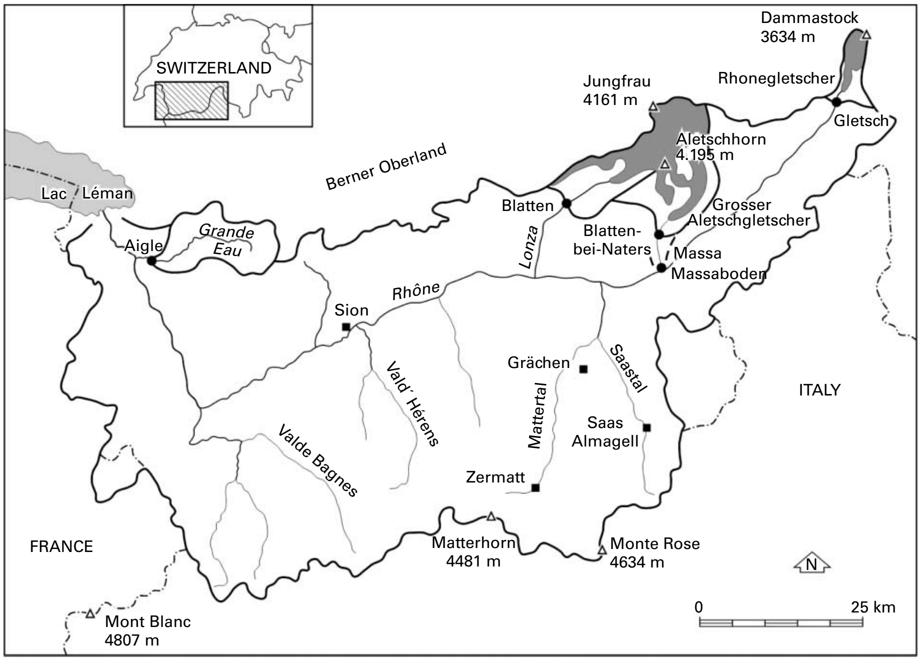

Figure 1 Locations of catchment areas nested in the Rhône basin, Valais, Switzerland. Gauging and meteorological stations, from which records have been used in this study, are indicated. Glacierised areas within the study basins are shaded

Measurements

Hydrometeorological records and climatic variables

Characteristics of the meteorological stations, from records for which climatic variables have been derived, are presented in Table 2. Locations of the meteorological stations in the upper Rhône basin are shown in Figure 1. The series of annual values of mean summer air temperature between May and September (T_{5-9}) can be used to indicate temporal patterns of energy availability for melting, that extracted from the long record observed at the Couvent des Capucins station at Sion having been found to correlate well both with temperature variables derived from records at other stations in the upper Rhône basin and with summer and annual discharges from glacierised sub-basins (Collins 1987, 1989b). Although located at a relatively low elevation in the Rhône basin, T_{5-9} at Sion can be taken as indicative of energy availability across the region. Measurements at Sion ceased in 1977, but subsequent values of T_{5-9} have been estimated from relationships between air temperature measured at Sion, Grächen and Saas Almagell. Precipitation in Alpine areas is far from uniform, but the record from the gauge at Zermatt probably provides a reasonable indication of the pattern of year-to-year variation over glacierised basins at higher elevations. Total annual precipitation between November and October (P_{11-10}) reflects build-up of winter snowpack before subsequent contribution to runoff on melting in spring, and liquid precipitation contributing to flow in summer.

River flow records

Annual runoff from each of the four basins is represented by Q_{1-12}, total discharge in the calendar year 1 January through 31 December. For the Massa, which drains the most highly-glacierised basin, between 88–96% of the annual runoff is discharged in the ablation season between 1 May and 30 September (Q_{5-9}). Relative to previous years, discharge of the Massa is unlikely to have been diminished since 1965 by as much as the 3.47% reduction in basin area might suggest, for relocation of the gauge excluded the portion of the ice-free basin at lowest elevation with minimum precipitation and hence limited specific discharge.

Temporal variations of climate and runoff

Climatic variation

Secular trends in climatic conditions influencing glacier decline from the maximum Little Ice Age extent are illustrated by plots of the climatic variables T_{5-9}, for Sion, Grächen and Saas Almagell, and P_{11-10}, for Zermatt, from the mid-nineteenth through the twentieth century (Figure 2). Amplitude of year-to-year variability of T_{5-9} was considerable throughout the series, based around underlying cyclical fluctuation. From warm years in the 1860s, mean quinquennial T_{5-9} had fallen about 2°C by the 1880s, before rising to a maximum at the end of the nineteenth century. A peak of 17.3°C in 1906 was an outlier from a downturn at the onset of the twentieth century. After a low of 15.9°C in 1914, the five-year

Table 2 Hydrometeorological measurements and climatic variables

Station	Elevation (m a.s.l.)	Length of record	Measurement	Climatic variable
Sion, Couvent des Capucins	549	1865–1977	Air temperature	Mean summer air temperature (T_{5-9})
Zermatt	1605	1888–2004	Precipitation	Total annual precipitation (P_{11-10})
Grächen	1617	1966–2004	Air temperature	T_{5-9}
Saas Almagell	1669	1968–1994	Air temperature	T_{5-9}

running mean of T_{5-9} climbed to reach a maximum of 18.4°C in the late 1940s, with an exceptionally warm individual summer in 1947 (19.77°C). Summer temperature then generally declined until the late 1970s (quinquennial mean of 16.8°C centred on 1979), with 1965, 1972 and 1977 particularly cool years. Recovery from the early 1980s has been sustained, to the series maximum five-year mean of 19.2°C in 1999–2003. T_{5-9} in 2003, the warmest summer (20.85°C) in the record, exceeded that of 1947 by 1.08°C.

Total annual precipitation (P_{11-10}) at Zermatt was also characterised by year-to-year variability (Figure 2). Very dry years at the end of the nineteenth century were followed by two decades in which the three wettest years in the 100-year series occurred. From the late 1920s to the early 1950s, precipitation was relatively low, accompanying generally warm summers. Wetter conditions returned alongside cooler summers from the late 1950s through to the early 1980s, 1979/80 being the wettest year since 1913/14. The years 1976/77 through 1980/81 had the highest quinquennial total annual precipitation in the record. Precipitation was then generally below average for much of the warm 1980s through 2000s. 2003/04 was the driest year (P_{11-10}) since 1893.

Ablation season runoff variation in the Massa

The record of runoff for the Massa, which drains the most highly-glacierised study basin (and the basin with the largest glacierised area), shows how, in the longer term, discharge from glaciers follows energy availability for melt in summer. Annual total discharge in the Massa for the months May through September (Q_{5-9}) varied substantially from year to year, Q_{5-9} mimicking fluctuations in T_{5-9}, as shown in Figure 2. Runoff increased substantially in response to warming between the 1930s and 1940s – an increase of 23.5% for a rise in decadal average T_{5-9} of 0.71°C. Ablation season discharge then declined by 21.7% from the 10-year period high (1941–1952) to the low (1972–1981), reflecting a fall in corresponding decadal mean summer air temperature of 1.06°C. Discharge in the 1970s was reduced by comparison with the 1930s by ~15%, with decadal T_{5-9} down by 0.4°C. The change in location of the Massa gauging station can account for only a small proportion of the reduction in flow. Runoff levels were restored with rising energy availability in the generally warm years since 1982. Quinquennial average summer runoff increased substantially (by 51%) between 1976–1981 (quinquennial minimum of $313.67 \times 10^6\,\mathrm{m}^3$) and 1999–2003 (maximum of $473.50 \times 10^6\,\mathrm{m}^3$) for a surprisingly large corresponding increase in T_{5-9} of 2.34°C.

Although the summer of 2003 was substantially warmer than that of 1947, Q_{5-9} of $605.94 \times 10^6\,\mathrm{m}^3$ in 2003 failed to exceed the series maximum, $631.62 \times 10^6\,\mathrm{m}^3$. Ablation season temperatures comparable with those of the 1940s and 1950s generally failed to raise Q_{5-9} to equivalent levels in the 1990s and 2000s. The third highest Q_{5-9} in the Massa was in 1928, an apparent anomaly. In that year T_{5-9} at Sion was about average (17.8°C) and P_{11-10} unexceptional, with 754 mm received at Zermatt. However, the mean July air temperature (22.9°C) was the highest recorded for that month at Sion. Also in 1928, Zermatt had the second driest June in the record and a very dry July, so that radiative melt under clear skies, having raised the transient snow line, would have produced exceptional melt over a wide expanse of bare ice in the Massaboden basin. The total discharge of the Massa was greater in the July of 1928 than in any other in the record.

Annual total runoff variation in the four study basins

Year-to-year variations of annual total runoff (Q_{1-12}) for the four study basins are shown in Figure 3. Broadly, runoff in the most heavily glacierised basins, Rhône and Massa, was coupled with energy availability for melting, declining to the mid-1970s and then recovering into the 1990s. Certain years stand out in these records as having total discharges higher than

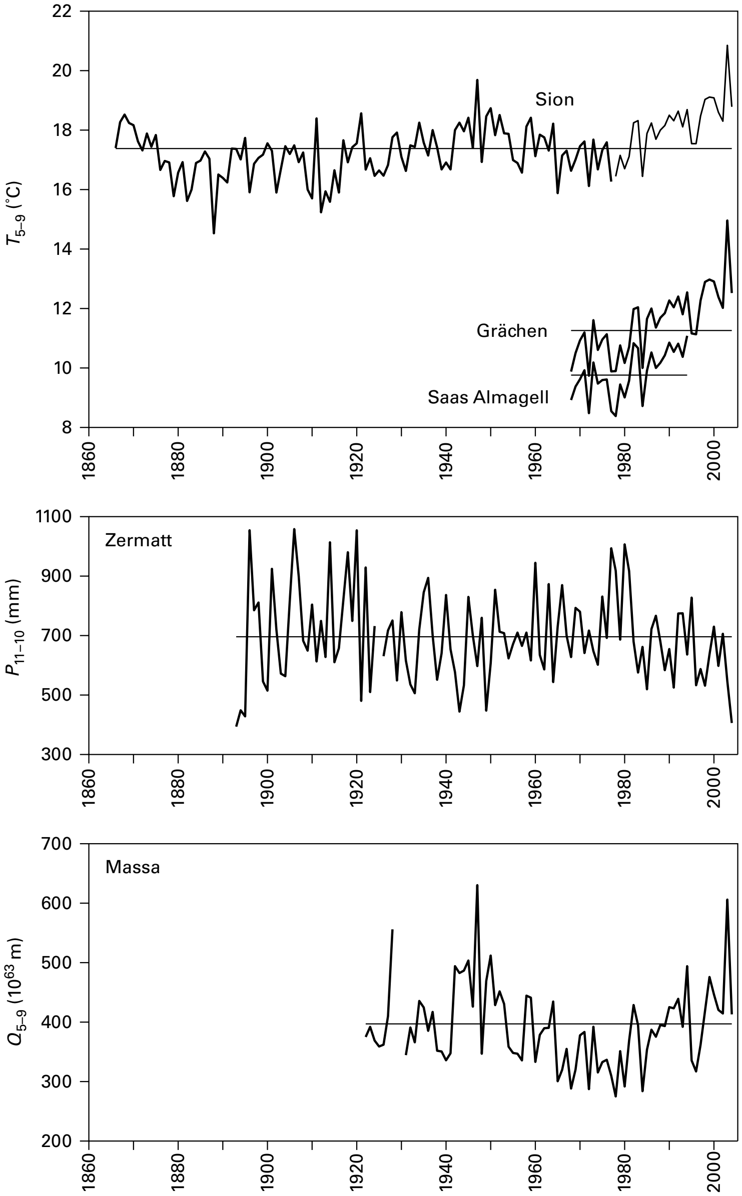

Figure 2 Year-to-year variation of mean summer air temperature (T_{5-9}) at Sion, Grächen and Saas Almagell (upper), annual total precipitation between November and October (P_{11-10}) at Zermatt (centre), and annual total discharge of the Massa in the months May through September (Q_{5-9}) (lower) in the period 1865–2004. From 1978 through 2004, T_{5-9} at Sion (thin line) was estimated from the records at Grächen and Saas Almagell. Recording of precipitation at Zermatt was interrupted in 1925. Discharge of the Massa was not measured in 1929 and 1930. The mean of each series is indicated by a horizontal line

those in surrounding years. Between 1956 and 2004, such prominent flows occurred in 1958, 1964, 1982, 1994, 1999 and 2003. Rank order of Q_{1-12} for these years is given in Table 3. The largest annual total discharge in the Rhône was in 1994, whereas in the Massa, flow in 2003, the warmest year, exceeded that in 1994 by 19.3%. Annual runoff in the Rhône was in general greater in the early than in the late 1990s, whereas runoff in the Massa continued to be enhanced.

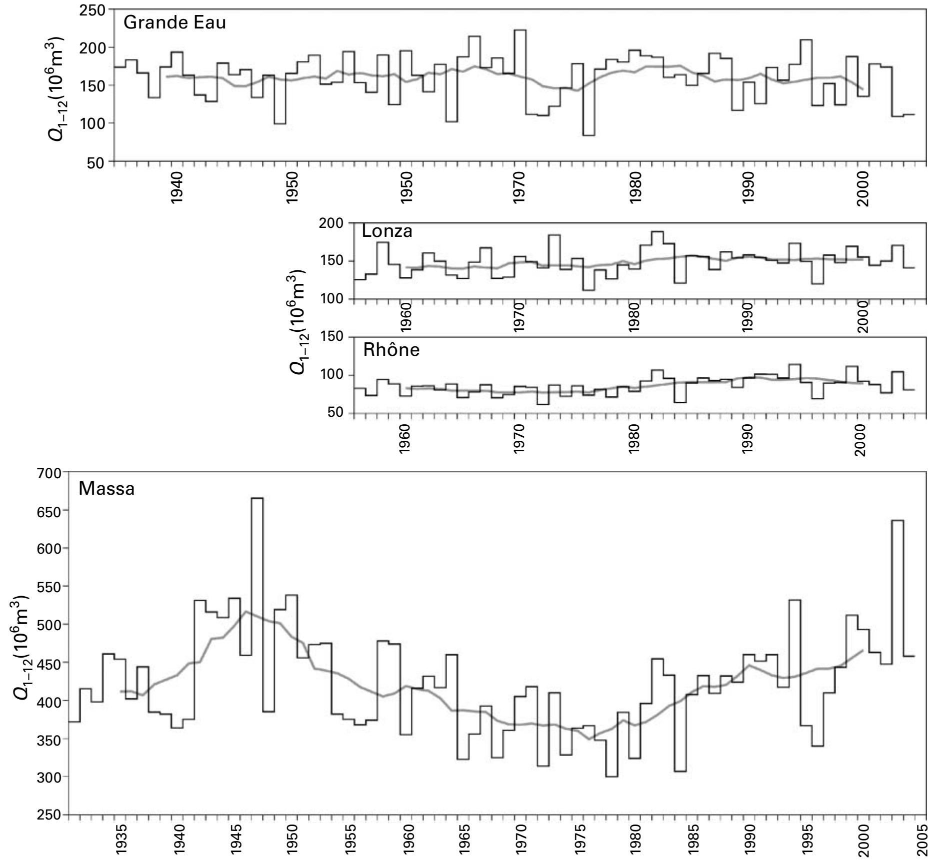

Figure 3 Year-to-year variations and five-year moving averages of annual total discharge (between January and December (Q_{1-12})) of the Grande Eau, Lonza, Rhône and Massa in the period 1930–2004

Annual runoff from the less-glacierised Lonza basin was sustained throughout the 1960s and 1970s, reaching a maximum in 1982. Runoff in subsequent warm summers remained in the same range. Flow in prominent years in the 1990s and 2000s barely exceeded levels reached in the 1950s (Table 3). Total discharge in the Lonza in 2003 was just higher than that in 1999 but less than in 1994.

In the least-glacierised basin, annual discharge of the Grande Eau generally reflected precipitation and not thermal conditions, rising to a maximum in the late 1960s, declining in the dry early 1970s, before increasing again in the late 1970s/early 1980s. During the warm period since 1982, runoff declined, again reflecting below-average precipitation inputs and

Table 3 Rank orders of years with prominent mean summer air temperatures at Sion and high total annual discharges in the study basins between 1956 and 2004

Rank (highest to lowest)	Massa (Q_{1-12})	Rhône (Q_{1-12})	Lonza (Q_{1-12})	Grande Eau (Q_{1-12})	Sion (T_{5-9})
1	2003	1994	1982	1970	2003
2	1994	1999	1973	1966	1999
3	1999	1982	1994	1995	1994
4	1958	2003	1958	1980	1964
5	1964	1958	2003	1960	1982
6	1982	1964	1999	1987	1958

high evaporation. Flow in the Grande Eau was much depleted in 2003. Particularly wet years stand out in the record: 1965/66, 1969/70, the period 1976/77 through 1980/81, and 1994/95. The year-to-year pattern of runoff in the Grande Eau tends to be the inverse of that from the highly-glacierised Massa basin. The small areal extent of ice-cover prevented even the considerable summer energy availability for melt in the 1990s and the first few years of the twenty-first century making an impact in offsetting the reduced runoff arising from low precipitation over the large ice-free zone.

Discussion

The underlying cyclical pattern of warming following the period of maximum extent of glaciers in the Little Ice Age indicated by the meteorological records from Sion and Zermatt parallel the general pattern experienced in the Alps (e.g. Beniston *et al.* 1994; Beniston 2000). Mean summer temperature has oscillated through about 2.5°C from the beginning of the twentieth century to the late 1940s, down to the late 1970s and then up again in the 1990s/2000s warm period. Whilst the 1940s warming was also associated with drier conditions, the warming experienced from the early 1980s was accompanied by significant reduction in precipitation, related to persistent blocking high pressure conditions across the Alps (Beniston and Jungo 2002).

From Little Ice Age maximum extents, individual glacier areas have been reducing since around 1850. Typically, the planimetric area of the Rhônegletscher was reduced in extent from 20.19 km^2 in 1850 to 17.60 km^2 in 1973, a loss of 12.8% of the area (Maisch *et al.* 1999). The glacierised area of the Rhône basin above the gauge at Gletsch (i.e. Rhônegletscher and other small bodies of ice) was then further reduced by 7.5% between 1977 and 2002. Loss of glacier area occurred at an accelerating rate in the warm and dry conditions existing from 1982. The glacierised area in the Massa basin, however, diminished only by 1.1% between 1977 and 2002 (Table 1), having previously lost 7.07 km^2 of ice surface area (5.2%) between 1934 and 1957. How removal each year of a layer (a volume) of ice from the ablation zone surface translates into loss of planimetric area depends on the geometry of glacier cross-sectional area. Glacier area will be reduced most readily where ablation area ice margins are thin. Each glacier will suffer different patterns of area loss for a given mass loss according to local physiography. Reduction in glacier area occurred throughout the twentieth century, including periods when energy availability for melting was reducing. For example, glaciers continued to lose mass during the cooling period between the 1940s and the late 1970s. Throughout the twentieth century, therefore, it appears that precipitation levels at high elevation were inadequate to maintain the flow of glaciers to lower elevations to offset the mass of ice lost through melting.

As glacier area is reduced, runoff from the glacierised portion of a basin will decline, as water yield is effectively determined by the product of the amount of melt per unit area and the surface area of the glacier over which melting takes place. Melt per unit area depends on the nature of the substrate which, for a given energy availability, is greater over ice than over snow, such that water yield is influenced by the relative proportions of the total glacier surface area made up of snow and ice. There are then three components of temporal variation in water yield from Alpine glacierised basins: (1) change in energy availability (indicated by summer temperature), (2) changes in overall glacier area, and, within that, changes in the relative areas of ice and snow over which energy is exchanged, which component dominates in more highly-glacierised basins, and (3) of more importance in less ice-covered basins, precipitation variation over the ice-free area. Strength and direction of relationships between climatic variables and runoff in the four basins are indicated by the matrix of correlation coefficients in Table 4. Change in glacierised area notwithstanding, the strength of positive association between air temperature and discharge increases with increasing basin glacierisation, whilst the strength of negative association between precipitation and runoff decreases.

Kasser (1981) and Chen and Ohmura (1990) considered that reduction in glacierised area had dominated the trend in runoff from Alpine glacierised basins. In the warm, dry years since 1982, runoff arising from ice-free areas of basins will have followed the same pattern as the Grande Eau. In this period, summer heat energy first enhanced flow from glaciers in the more highly-glacierised basins in 1982, following the dry winter of 1981/1982, allowing early ascent of the transient snowline on glaciers which exposed broad swathes of ice to sustained melt. Runoff in that year was also enhanced by summer rainfall. Runoff from the Lonza basin failed subsequently to attain the 1982 peak, although discharge in 2003 was greater than in 1999. The warm summers in 1999 and 2003 produced prominent flows on falling trend in the Rhône, discharge of which had peaked in 1994. Total discharge in the Massa was greater in 2003 than in 1994 (Figure 3). The correlation coefficient between Sion T_{5-9} and Q_{1-12} for the Rhône at Gletsch declined from 0.75 for 1956–1999 to 0.57 for 1982–2004, whilst remaining at 0.54 for the Lonza and increasing from 0.90 to 0.93 for the Massa (Table 4). Loss of ice surface area at the lower margins of the ablation zone has probably been offset by the transient snowline progressively ascending sooner to higher elevations, exposing additional areas of ice, or firn, to melt in warmer years. Expansion of the area of bare ice exposed to melt with the rise of the transient snowline will enhance runoff. The additional area of ice so exposed to melt depends on the hypsometry and vertical extent of the glacier. Similarly, in warmer summers, increased air temperature at higher elevations will enhance snowmelt, for runoff the effect being amplified by the hypsometry of the snow surface.

As precipitation increases with elevation, glaciers originating and with large areas at higher elevations will accumulate sufficient mass to withstand melting and hence flow further down slope to lower elevations. The upper limit of glacierisation depends on topography and is fixed by summit elevations. The altitudinal limits of the glacierised areas in each of the study basins are plotted as a vertical line with respect to percentage glacierisation in Figure 4.

The Massa basin contains the largest glacierised area, which starts at a higher, and terminates at a lower, elevation than the other three glaciers. Glaciers around the rim of the Grande Eau basin are small, poorly nourished, and have limited vertical extent between 2450 and only 3000 m a.s.l. A schematic distribution of elevation ranges of individual glaciers in the upper Rhône catchment is shaded in Figure 4. Assuming, in a fairly warm summer, that the transient snow line across the upper Rhône rises to a final elevation of about 3300 m a.s.l., snow will have been removed from all the glacierised area in the Grande Eau basin. The ice area over which heat can be exchanged is at a maximum, but is small, and the limited glacier component of runoff depends on energy availability only. In a very warm ablation season, with the transient snow line at about 3500 m, the same small area will be exposed to melt. In the Rhône basin above Gletsch, as the transient snow line rises up the glacierised area, runoff production is related to both energy input and changing ice/snow surface area ratio. In this basin, in exceptionally warm years, winter snow accumulation will be removed from all the glacierised area. The Lonza basin has an additional 260 m vertical extent of glacierised area above the highest point in the Rhône basin, and so, as in the Massa basin, rising of the transient snow line ever higher continues to expose a broader area of ice and firn, enhancing melt. Warmer temperatures melt snow still higher.

The view of Collins (1989a) that amounts of runoff from Alpine glacierised basins would probably be maintained even though glaciers continued to retreat appears only partially to have been borne out, runoff in the Lonza and Rhône having started to decline before the exceptionally warm 2003. The Massa basin has a sufficient area of snow-covered ice at high

Table 4 Matrix of correlation coefficients showing inter-relationships between climatic variables and runoff for the periods indicated

	Sion (T_{5-9})	**Zermatt (P_{11-10})**	**Grande Eau (Q_{1-12})**	**Lonza (Q_{1-12})**	**Rhône (Q_{1-12})**	**Massa (Q_{1-12})**
Sion (T_{5-9})	–	−0.50 1956–1999	−0.30 1956–1999	0.54 1956–1999	0.75 1956–1999	0.90 1956–1999
Zermatt (P_{11-10})	−0.46 1935–1999	–	0.61 1956–1999	−0.14 1956–1999	−0.21 1956–1999	−0.41 1956–1999
Massa (Q_{5-9})	0.85 1935–1999	–	–	–	–	0.99 1935–1999
Grande Eau (Q_{1-12})	−0.25 1935–1999	0.62 1935–1999	–	–	–	−0.18 1935–1999
	−0.37 1982–2004	–	–	–	–	–
Lonza (Q_{1-12})	0.54 1982–2004	–	0.20 1982–2004	–	0.82 1982–2004	–
Rhône (Q_{1-12})	0.57 1982–2004	–	0.26 1982–2004	–	–	–
Massa (Q_{1-12})	0.86 1935–1999	−0.38 1935–1999	−0.09 1956–1999	0.66 1956–1999	0.88 1956–1999	–
	0.93 1982–2004	–	−0.19 1982–2004	0.66 1982–2004	0.70 1982–2004	–

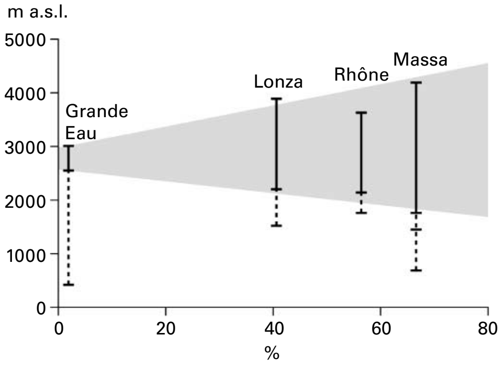

Figure 4 Elevations of upper and lower limits of glacierised areas plotted against percentage basin glacierisation. Broken lines indicate the vertical distances between the gauges and respective glacier termini. The gauging station on the Massa was relocated upstream at higher elevation in 1965. The shaded area shows schematically the ranges of elevations within which glaciers are distributed in the upper Rhône basin

elevation contributing to melt, but yet to yield enhanced melt when the ice becomes exposed, that at least some of the decline in meltwater production resulting from the loss of ice surface area in the ablation zone through glacier recession will continue to be offset.

The position of a gauging station along the length of a river defines basin area, and hence with the glacier area contained in the basin determines percentage glacierisation. Percentage glacierisation of basin is an arbitrary characteristic. As shown in Figure 4, the basin of the Rhône at Gletsch is more highly-glacierised (56.4%) than that above Blatten on the Lonza (40.6%), but the area of ice included is smaller (20.3 km^2 against 28.4 km^2 in 2002) and the vertical extent of the glacierised area limited. Glacierised basin hypsometry may prove a useful framework for assessing future water yields from mountain basins as glaciers continue to decline.

Conclusion

Since the Little Ice Age maximum, areal extent of glacier cover in sub-basins of the upper Rhône catchment reduced considerably in response to two major cycles of climatic warming during which energy availability for melting generally increased and precipitation declined. In basins with limited glacierisation, and the glacier areas located at relatively low elevations, year-to-year variations in total runoff followed those of total annual precipitation. Although the quantity of water produced by melt per square metre of ice will be higher than the water yield (precipitation–evaporation) per square metre of ice-free area, the product of specific yields and areas of respective portions of basin favours the ice-free area. The larger the basin percentage glacierisation, the more the general pattern of runoff was influenced directly by the cycles of warming. In more highly-glacierised basins the relationship between runoff and precipitation tends to be negative.

Loss of surface area by recession of the lower margins of glaciers has tended to reduce runoff from glacierised sub-basins of the upper Rhône. This effect has, however, been offset to an extent where large glaciers descend from high elevations and have considerable vertical extents. Progression higher of the transient snowline extends the area of bare ice (and firn) exposed to melt, replacing some of the area of ice lost from the ablation zone. Such upward progression is favoured in years in which limited accumulation of winter snow pack is followed by warmer summers. Melting of snow also extends higher into the accumulation zone during warmer summers. Runoff from the more highly-glacierised Alpine basins was therefore strongly influenced by energy availability for melting, with high levels of discharge produced in particularly prominent warm years in the record, during the 1940s/1950s and in the 1980s through 2000s. Although runoff in the second warming period generally reached levels previously attained in the 1940s, overall decline in glacier planimetric area limited peak year discharges after 1982.

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