Climate Variability and Change—Hydrological Impacts (Proceedings of the Fifth FRIEND World Conference held at Havana, Cuba, November 2006), IAHS Publ. 308, 2006.

Variability of runoff from Alpine basins

DAVID N. COLLINS

Alpine Glacier Project, School of Environment & Life Sciences, University of Salford, Salford Crescent, Manchester M5 4WT, UK

d.n.collins@salford.ac.uk

Abstract Year-to-year variability of runoff from three moderately-glacierized (36–66% ice cover) and two (near-)ice-free (0–1.9%) headwater basins in the Alpine Aare and Rhône basins, Switzerland, was assessed for 50 years from 1956 to 2005. Variability, as coefficient of variation, was less in moderately-glacierized than in (near-) ice-free precipitation-influenced basins, but increased in basins with between 40 and 66% glacierization as energy-availability for snow/icemelt dominated. Mean summer air temperature increase of 1.13°C between 1956–1980 and 1981–2005, coupled with a 13% reduction in mean total annual precipitation, was associated with decreased runoff variability in basins having between 0 and 40% glacierization but with increased variability in more highly glacierized basins.

Key words coefficient of variation; runoff variability; glacierized basin; climatic variation

INTRODUCTION

Annual accumulation and melting of stable winter snowpack, together with summer glacier ice ablation, account for distinctive runoff characteristics in high mountain basins. In ice-free montane basins, maximum monthly discharge occurs in spring, annual runoff is less than annual total precipitation, and year-to-year variations in runoff follow those of precipitation. In glacierized basins, the greater the percentage ice cover, the later into summer is maximum monthly discharge delayed, the higher the annual runoff, which can be more than, equal to, or less than, annual precipitation, depending on changes in storage of water as glacier ice, and the more runoff variability is influenced by intra-annual changes in thermal energy available for melting. Runoff variability is negatively related to percentage basin ice-cover up to a point (e.g. Krimmel & Tangborn, 1974; Fleming & Clarke, 2005), but then as glacierization increases above about 20–25%, the relationship turns positive (Walser, 1960; Tvede, 1982). In basins with some but not extensive ice-cover, glaciers effectively moderate intra-annual variations in river flow, in cooler years by runoff arising from precipitation over the large ice-free area offsetting reduced glacier melt, and in warm dry summers through enhanced melt making up for reduced precipitation.

Thermal energy availability interacting with snowfall over the glacier ablation area strongly influences runoff variability in moderately-glacierized basins (Collins & Taylor, 1990), ice-free areas predominantly located at lower elevations producing limited runoff from less precipitation. In warm summers following dry winters, the transient snow line rises sooner and higher up-glacier, allowing more ice melt over a wider area than in years in which cool summers follow snowy winters. Runoff variability in long series will also be affected by changes in both overall glacier surface area, and area of ice exposed to melt as loss through marginal recession may be offset by general rising of the transient snow line (Collins, 1989a).

The aim of this paper is to describe the variability of runoff from moderately-glacierized Alpine basins during the 50-year period 1956–2005. Basins with glacierization in the range 35–70% were selected, and referenced against ice-free/near-ice-free basins. Overall glacier areas declined throughout the period, initially in spite of cool wet conditions which reduced runoff from more highly-glacierized basins. From the early 1980s, warmer summers and relatively dry winters, resulting from high pressure anomalies over Central Europe (Beniston & Jungo, 2002), generally enhanced runoff from moderately-glacierized basins into the early 1990s. The more extensively-glacierized the basin the more increased runoff was sustained into the 2000s (Collins, 2005). For basins in Switzerland with more than 10% glacierization, an upward trend in runoff was detected between the 1970s and 2000s (Birsan *et al*., 2005).

MEASUREMENTS

Five headwater basins in the Rhône and Aare catchments, Switzerland, basins for which runoff variability from the 1950s to the mid-1980s had previously been assessed (Collins, 1989a, Collins

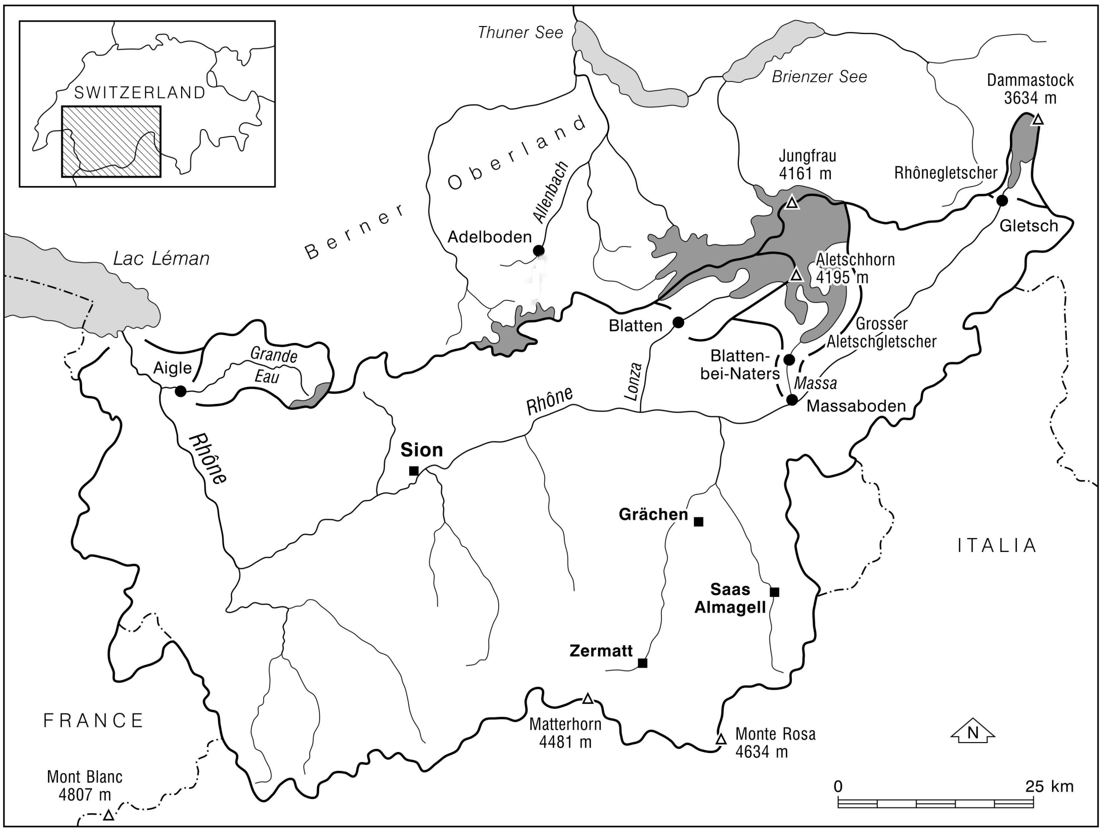

Fig. 1 Locations of the five study basins and meteorological stations from which records have been analysed in the upper Aare and upper Rhône basins, Switzerland.

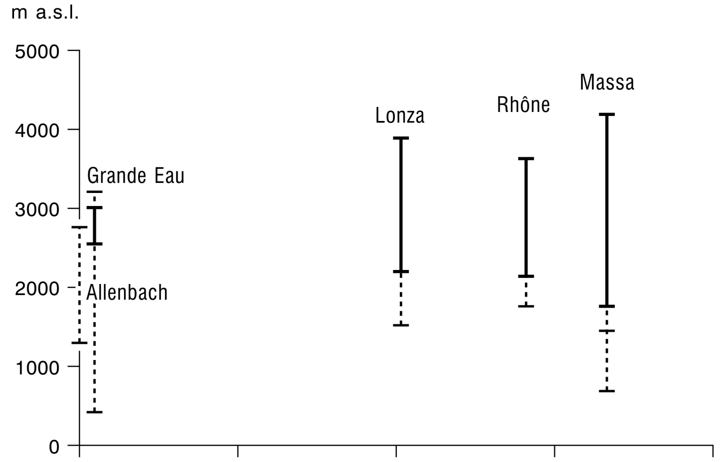

Fig 2 Elevations of gauging stations, lower and upper limits of glacierized areas (solid lines) and highest points in each study basin plotted against percentage basin glacierization.

& Taylor, 1990), were selected for the study (Fig. 1). All five basins are exposed to the same pattern of climatic influences. Basin characteristics are shown in Fig. 2 and Table 1. Runoff in the Grande Eau is slightly influenced by water storage. The Massa was gauged at Massaboden to 1964, before the station was moved upstream to Blatten-bei-Naters. Basin area was reduced by 3.47%, but discharge measurements in the Massa have not been adjusted. Otherwise, records are homogeneous and of natural flow regimes. Annual runoff ($Q_{1\text{-}12}$) is represented by total discharge in a calendar year, 1 January through 31 December.

Although Alpine precipitation is far from being uniformly distributed, total annual precipitation at Zermatt (1632 m a.s.l.) (Fig. 1) was taken as indicative of year-to-year variations

Table 1 Characteristics of basins: glacierized areas and runoff, 1956–2005.

River/Gauging station	Basin area (km²)	Basin glacierization (year)	(%)	Mean runoff (m)
Allenbach/Adelboden	28.8		0.0	1.312
Grande Eau/Aigle	132.0	1977	1.9	1.190
		2002	1.8	
Lonza/Blatten	77.8	1977	40.6	1.905
		2002	36.5	
Rhône/Gletsch	38.9	1977	56.4	2.218
		2002	52.2	
Massa/Massaboden	202.0	1957	64.1	2.112
Massa/Blatten-bei-Naters	195.0	1957	66.4	
		1977	66.6	
		2002	65.9	

over the study basins. Precipitation between November in year *n* and October in year *n* + 1 ($P_{11\text{-}10}$) reflects winter snow pack accumulation contributing to runoff on melting in spring, plus liquid precipitation contributing to summer flows. Mean summer air temperature between May and September ($T_{5\text{-}9}$) usefully indicates energy availability for melting. A part-synthetic record of $T_{5\text{-}9}$ for Sion (Couvent des Capucins) (542 m a.s.l.) has been derived from observations at Sion, Grächen and Saas Almagell, as described by Collins (1989a). Overall percentage glacier cover of a basin (Table 1) has been taken from the *Hydrologisches Jahrbuch der Schweiz* (e.g. Bundesamt für Wasser und Geologie, 2003).

BASIN CHARACTERISTICS AND RUNOFF

Whilst glacierized area in a basin increases with upper basin limit elevation (Table 1, Fig. 2), percentage glacierization is also influenced by the distance from glacier terminus to downstream gauging station location. Basins with gauging stations at low elevations also contain areas receiving lower precipitation contributing less runoff, which may explain why mean annual runoff in the Grande Eau and Massa was lower than in the Allenbach and Rhône respectively (Table 1). Area, hypsometry and elevation range of glaciers, all ice-cover properties influencing meltwater production, are not simply related to percentage glacierization.

For the (near-)ice-free basins, maximum monthly runoff occurred in May in both Grande Eau and Allenbach, with averages of 52.5 and 63.6%, respectively, of total annual runoff occurring during snowmelt in the four months April–July (Fig. 3). The smaller percentage for Grande Eau reflects more runoff in winter as a result of snowpack instability at lower elevations. With higher basin glacierization, maximum monthly runoff was delayed to July in Lonza and Rhône, and to August in the Massa, with averages of 85.1, 88.2 and 92.3%, respectively, of total annual runoff occurring in the five summer months May–September. Including October as a sixth summer month, these percentages of ablation season/total runoff become 90.7, 93.4 and 97.1, emphasizing glacial domination of runoff once ice covers a substantive portion of a basin.

In the 50-year period 1956–2005, glacier cover declined in all four basins with glaciers. In the Massa basin, Grosser Aletschgletscher was reduced in area by about 1 km^2 (0.8 %). From 1977, Rhônegletscher lost about 1.6 km^2 (7.3%), Langgletscher (in the Lonza basin) about 3.2 km^2 (10.1%) and Glacier de Pierredar (Grande Eau) 0.13 km^2 (10.6%), the percentage loss increasing with decreasing elevation. Such changes in glacier area will have influenced meltwater production and hence have tended to reduce annual runoff.

VARIABILITY OF RUNOFF

Coefficient of variation (CV), the ratio of standard deviation to mean, is usually used for comparisons of year-to-year variability of runoff between basins (e.g. Collins, 1989a). Annual runoff variability in the 50-year period was greatest in the Grande Eau (CV = 0.210), slightly higher than in the ice-free Allenbach (CV = 0.190) (Fig. 4). The CV of $P_{11\text{-}10}$ at Zermatt for the same period was

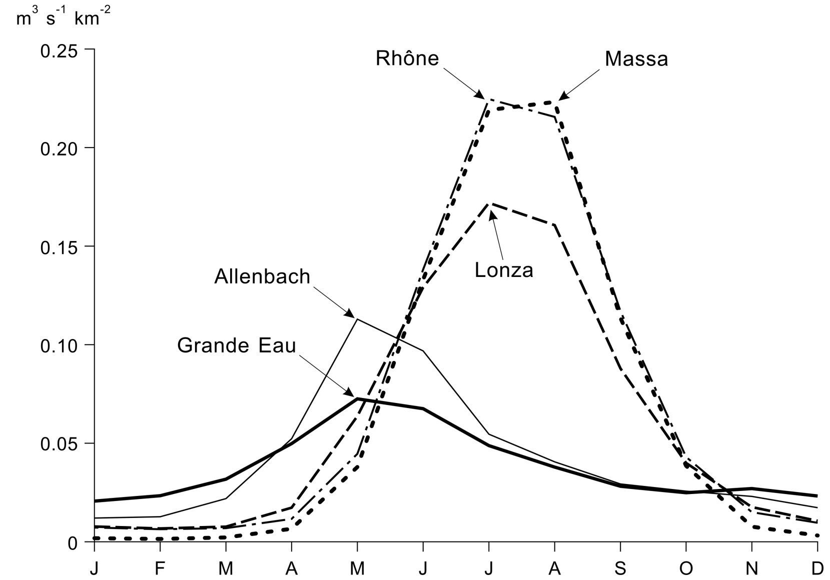

Fig. 3 Mean monthly specific discharge in the Allenbach, Grande Eau, Lonza, Rhône and Massa rivers for the period 1956–2005.

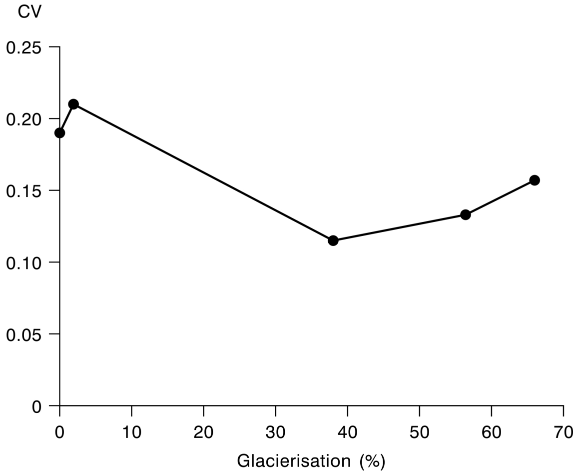

Fig. 4 Coefficient of variation (CV) of total annual runoff from the five study basins for the period 1956–2005 as a function of percentage basin glacierization.

close at 0.191. Variability of runoff was least in the Lonza (CV = 0.115) at a mean of 38.5% glacierization, but then increased with increasing glacierization to 0.157 in the Massa, at 66.3% ice cover the most highly glacierized basin although year-to-year variability of flow was still less than in the (near-)ice-free basins.

Monthly runoff totals were generally more variable from year to year than annual runoff, irrespective of basin glacierization (Fig. 5). Minimum variability of monthly flow occurred in July or August, months with the highest runoff, in the three moderately-glacierized basins. Months with considerable variability in flow were March, April, May, September, October and November, months marginal to the main ablation season. March, April and November are months in which absolute amounts of discharge are small, and hence variability of flow in those months contributed little to overall year-to-year variability of annual total runoff. Warmer springs, particularly those following drier winters, enhanced runoff totals in May and increased dispersion during the 50 years. Again in warmer years, the ablation season lengthened as energy availability extended into autumn. Variability of individual monthly runoff was in general greater in the (near-) ice-free than in the moderately-glacierized basins. Year-to-year variability in monthly runoff from the (near-) ice-free basins was also inversely related to volume of flow, lower in the spring months and higher in the autumn. November runoff was exceptionally variable, as in warmer years rain formed runoff rapidly, but in cooler years snow had already started to accumulate, delaying runoff until spring.

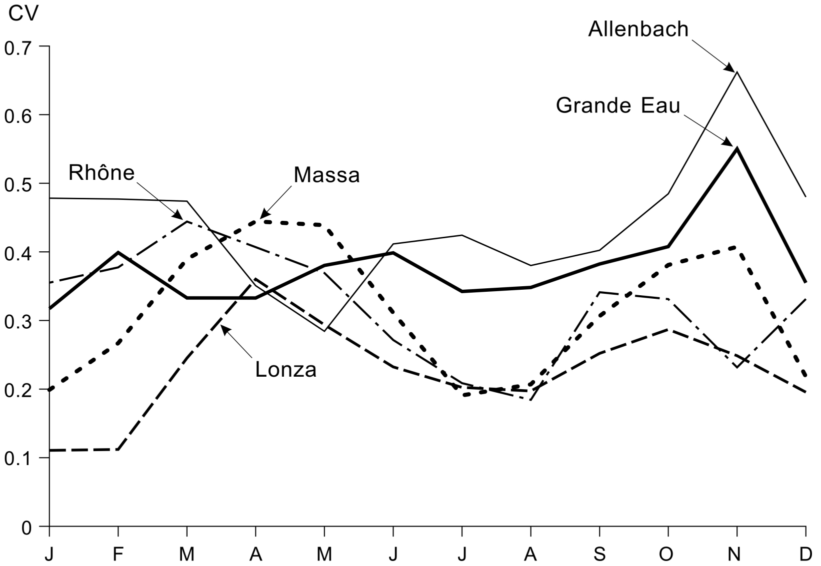

Fig. 5 Coefficients of variation (CV) of total monthly runoff for the Allenbach, Grande Eau, Lonza, Rhône and Massa rivers for the period 1956–2005.

CLIMATIC FLUCTUATION AND RUNOFF VARIABILITY

Division of the 50-year period into two equal-length sub-periods, 1956–1980 and 1981–2005, although arbitrary, allows consideration of the impact of climatic fluctuation on runoff variability. Summer 1982 was the first of many warm summers that occurred in the 1980s through 2000s. 1956–1980 was generally cool and wet, but in 1981–2005, $T_{5\text{-}9}$ at Sion was 1.13°C higher and mean precipitation at Zermatt was down by 13% (Table 2). Both mean annual runoff and year-to-year variability were lower in the (near-) ice-free basins in the second sub-period. In the glacierized basins, mean runoff increased into the warmer sub-period by between 8 and 16%, even though glacier areas had been reduced. Percentage increases in runoff above levels during the first sub-period were larger the higher the basin glacierization. Runoff variability in the warmer sub-period was lower in the Lonza but higher in both Rhône and Massa than in 1956–1980.

Table 2 Mean values (and coefficients of variation) of climate and runoff variables for the 25-year periods 1956–1980 and 1981–2005.

			1956–1980	1981–2005
Sion	$T_{5\text{-}9}$	°C	17.21	18.34
Zermatt	$P_{11\text{-}10}$	mm	740.1 (0.179)	646.0 (0.177)
Allenbach	$Q_{1\text{-}12}$	$\times 10^6$ m^3	37.96 (0.221)	37.62 (0.185)
Grande Eau	$Q_{1\text{-}12}$	$\times 10^6$ m^3	159.95 (0.223)	154.21 (0.190)
Lonza	$Q_{1\text{-}12}$	$\times 10^6$ m^3	142.15 (0.114)	154.06 (0.099)
Rhône	$Q_{1\text{-}12}$	$\times 10^6$ m^3	80.25 (0.095)	92.29 (0.125)
Massa	$Q_{1\text{-}12}$	$\times 10^6$ m^3	380.50 (0.129)	443.44 (0.142)

DISCUSSION

Throughout the 50-year period, precipitation appears generally to have been insufficient to offset ablation such that glaciers continued to lose mass and reduce in area, and precipitation declined during the warmer sub-period. By comparison with the ice-free Allenbach, minimal glacier cover had negligible impact on runoff variability in the Grande Eau. In the moderately-glacierized basins, for the 50-year period, runoff variability increased with increasing ice cover, but was lower for all three basins than for the (near-)ice-free basins, and also less than year-to-year variability of precipitation. As runoff in such moderately-glacierized basins is largely determined by energy availability, tempered to an extent by precipitation on the glacier, year-to-year variability of energy availability must be less than that of precipitation. Coefficients of variation of summer energy availability (as positive degree days) at stations in the upper Rhône basin were 0.042 for 1935–1964 and 0.078 for 1968–1986 (Collins, 1989b).

Warm summers in the second sub-period produced exceptional annual total flows from the moderately-glacierized basins, widening the range of amounts of runoff by raising the upper margin. In basins in which the glacierized area extends to high elevation, the zone of snow and ice over which melting occurs can expand upwards in warmer summers, so increasing the area across which meltwater is produced. Expansion upwards of the melting zone and early rising of the transient snow line to high elevation contribute to enhanced runoff from such basins in warmer summers. Upward widening of the melting zone to higher elevation initially at least offsets ice area loss through glacier recession at lower elevations, a condition which can only continue until the upper limit of the glacierized area has been reached. Detailed analysis of runoff from these glacierized basins suggests that flow in both Lonza and Rhône had already started to decline before 2003, the year with the warmest summer in the 50-year period (Collins, 2005). As shown in Fig. 2, the position of a gauging station along the length of a river defines basin dimensions, and hence percentage glacierization. Percentage basin glacierization is thus an arbitrary characteristic, and, whilst continuing in widespread use as a framework for evaluation of water resources in glacierized basins (e.g. Fleming & Clarke, 2003; Kaser *et al.*, 2003), it is not necessarily indicative of the hypsometry, planimetric dimensions or elevation range of the glacierized area, the characteristics which actually influence meltwater production and annual runoff from a glacierized basin.

CONCLUSION

In Alpine headwater basins of the Aare and Rhône, annual total runoff broadly increases as both basin elevation and basin glacierization increase. The month with the highest total flow is progressively delayed from May to August as basin glacierization increases. Year-to-year variability of annual runoff in ice-free and near-ice-free basins is about the same as that of annual total precipitation. In moderately-glacierized basins, runoff variability, whilst remaining considerably less than in ice-free basins, has been shown to increase as basin glacierization increases between about 38 and 66% ice-cover, influenced by year-to-year variability in thermal energy available for melting, which must be less than the variability of precipitation. In that range of ice-cover, variability of monthly total runoff is minimized in July and August, the months with the highest total discharge, and maximized in the months before and after the main ablation season. Availability of energy for producing runoff in May and September makes a considerable contribution to year-to-year variability of annual total runoff. In (near-)ice-free basins, exceptionally high monthly runoff variability occurs in November, a low flow month, in which runoff amount is influenced by whether thermal conditions lead to stable snow pack accumulation or rainfall-induced rapid runoff.

Between the 25-year sub-periods, 1956–1980 and 1981–2005, a 1.13°C rise in mean summer temperature, 13% reduction in mean total annual precipitation, and small reductions in glacierized areas, decreased runoff variability in basins with 0–40% glacierization, but resulted in increases in more highly glacierized basins. Mean annual flows from moderately-glacierized basins (40–66% glacierization) were enhanced in the second sub-period, as, in warmer summers, areas of snow and ice at higher elevations were exposed to melt. As percentage glacierization is arbitrarily defined by gauging station location, hypsometries and elevation ranges of glacierized areas may provide a more useful framework for assessing future reliability of water resources in glacierized mountain areas.

Acknowledgements The assistance of Bundesamt für Wasser und Geologie, and MeteoSchweiz, in making available discharge and meteorological records respectively, and of N. Scarle, in producing the diagrams, is gratefully acknowledged.

REFERENCES

Beniston, M. & Jungo, P. (2002) Shifts in the distributions of pressure temperature and moisture and changes in the typical weather patterns in the Alpine region in response to the behaviour of the North Atlantic Oscillation. *Theoretical and Appl. Climatol.* **71**, 29–42.

Birsan, M.-V., Molnar, P., Burlando, P. & Pfaundler, M. (2005) Stream flow trends in Switzerland. *J. Hydrol.* **314**, 312–329.

Bundesamt für Wasser und Geologie (2003) *Hydrologisches Jahrbuch der Schweiz 2002*. Bern, Switzerland.

Collins, D. N. (1989a) Hydrometeorological conditions, mass balance and runoff from Alpine glaciers. In: *Glacier Fluctuations and Climatic Change* (ed. by J. Oerlemans). Kluwer, Dordrecht, The Netherlands.

Collins, D. N. (1989b) Influence of glacierisation on the response of runoff from Alpine basins to climate variability. (Conference on Climate and Water). *Publications of the Academy of Finland* **9/89**(1), 319–328.

Collins, D. N. (2005) Climatic variation and runoff in mountain basins with differing proportions of glacier cover. In: *Proceedings Fifteenth Northern Research Basins Symposium*, 21–30.

Collins, D. N. & Taylor, D. P. (1990) Variability of runoff from partially-glacierised Alpine basins. In: *Hydrology in Mountainous Regions. 1 Hydrological Measurements, the Water Cycle* (ed. by H. Lang & A. Musy), 365–372. IAHS Publ. 193. IAHS Press, Wallingford, UK.

Fleming, S. W. & Clarke, G. K. C. (2003) Glacial control of water resource and related environmental responses to climatic warming: empirical analysis using historical streamflow data from north-western Canada. *Can. Water Resour. J.* **28**(1), 69–86.

Fleming, S. W. & Clarke, G. K. C. (2005) Attenuation of high-frequency interannual stream flow variability by watershed glacial cover. *J. Hydraul. Engng* **131**, 615–618.

Kaser, G., Juen, I., Georges, C., Gomez, J. & Tamayo, W. (2003) The impact of glaciers on the runoff and the reconstruction of mass balance history from hydrological data in the tropical Cordillera Blanca Peru. *J. Hydrol.* **282**, 130–144.

Krimmel, R. M. & Tangborn, W. V. (1974) South Cascade Glacier: the moderating influence of glaciers on runoff. In: *Proceedings of Western Snow Conference* 42, 9–13.

Tvede, A. M. (1982) Influence of glaciers on the variability of long runoff series. *Proceedings Fourth Northern Research Basins Symposium,* 179–189.

Walser, E. (1960) Die Abflussverhaeltnisse in der Schweiz waehrend der Jahre 1910 bis 1959. *Wasser- und Energiewirtschaft* **8/9/10**, 197–214.