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Outburst and Rainfall-induced Peak Runoff Events in Glacierised Alpine Basins

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ABSTRACT

The impact of rainfall on runoff from the highly glacierised basins containing Findelengletscher and Gornergletscher, Pennine Alps, Switzerland, is assessed for the periods May through September 1987 and 1993. Several major rainstorms produced high peak discharges in both seasons. Runoff response to prolonged heavy rainfall varied during the ablation season in both basins, but also differed between the two. Annual outbursts from the ice-dammed Gornersee also produced peak discharges from Gornergletscher. The transient snowline partitions a glacierised basin into snow-covered and snow-free portions which respectively retain and return rapidly to runoff both meltwater and rain. Elevation of the zero-degree Celsius isotherm in the atmosphere interacts with basin hypsometry to determine the proportion of the catchment area that receives rain in a given event. Progressive rise of the transient snowline in summer increases the size of the snow-free area, and hence the area of basin, which rapidly responds to rainfall. Heavy rainfall appears to have produced an outburst from Findelengletscher in September 1993. The largest rainfall-induced floods are most likely to occur in summer between mid-July and late-August, terminating periods of elevated air temperature, when thermally induced runoff is at a maximum and subglacial drainage pathways are well-developed, or when rainfall induces outbursts in spring and late summer at times of declined internal drainage capacity.

Key words: Glacier outburst flood, transient snowline, basin hypsometry, rainfall, glacierised basin.

INTRODUCTION

Peak runoff events in rivers draining from glaciers and glacierised basins in alpine areas result from both extreme hydrometeorological conditions and sudden outbursts of water stored in marginal ice-dammed lakes or in sub-/en-glacial pockets. Infrequent, sudden and short-lived outburst floods can be considerably greater in magnitude than peak events produced by high melt rates or rainfall in summer, but are characteristic only of certain glaciers. Hydrometeorologically induced floods are, however, ubiquitous, and weather conditions leading to periods of sustained high ablation rates or to sustained heavy precipitation events affect broad swaths of Alpine terrain. According to Haeberli (1983), though, few glacier floods result from or are associated with heavy precipitation. Röthlisberger and Lang (1987) considered that occurrences of events involving high-intensity rainfall had been rare at elevations above 2500 m a.s.l. in the European Alps.

Occurrences of sustained heavy precipitation have affected high elevation basins in the Alps during the warm summers of the 1980s and 1990s. Floors of Alpine valleys to which rivers descend down steep slopes from highly glacierised high-altitude basins have been inundated on several occasions as a result of heavy rainfall events accompanying the passage of storms as indicated in Table 1. Annual maximum flows induced by rain to high elevation in unregulated rivers draining partially glacierised basins in parts of the Swiss Alps in 1987 and 1993 had recurrence intervals in the range 10–30 years (Landeshydrologie und -geologie 1988, 1991, 1994). High intensity and sustained heavy rainfall events at high

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Table 1. Major rain-induced flood events in Alpine glacierised basins in the 1980s and 1990s.

Date	*Basin/range/area*	*References*
1–8 July 1987	Northern Switzerland	Zeller and Röthlisberger (1988)
14–19 July 1987	Lombardi, Italy Eastern Switzerland	Chardon (1990) Landeshydrologie und-geologie (1988, 1991)
23–25 August 1987	Alpine Switzerland	Landeshydrologie und-geologie (1988, 1991); Rey and Dayer (1990); Collins (1995, 1998a)
22–24 September 1993	Upper Rhône basin, Switzerland	Landeshydrologie und -geologie (1994); Collins (1998b)
1–8 October 1993	Ticino, Switzerland	Landeshydrologie und -geologie (1994)
5–6 November 1994	Piemonte, Italy	Pangallo (1995)
24–26 July 1996	Upper Arve basin, Mont Blanc, France Val Ferret, Switzerland	Cerutti (1997); Chaverot and George (1998) Rey and others (1998)

elevation sites triggered debris flows and landslides as well as producing floods, for example in the Swiss Alps in 1987 (Zimmermann 1990) and 1993 (Rebetez et al. 1997). More than half of the glacier floods listed by Haeberli (1983) were caused by outbursts of marginal lakes or sudden ice-dam breaks, the others being ruptures of en- or subglacial water pockets.

During winter months precipitation falls as snow throughout almost all the range of Alpine basin elevations above 2000 m a.s.l. This snow largely accumulates as a stable pack until the onset of melt in spring, contributing some of the minimal winter discharge. During summer, precipitation can have an immediate effect on runoff. Depending on whether precipitation occurs in liquid or solid form, the usual characteristic, serrated, diurnally varying, thermally produced meltwater hydrograph may respond by increasing or decreasing respectively. Whilst heavy rainfall over glacierised basins during the ablation season evidently has considerable impact on runoff, magnitudes of peak rainfall-induced discharges depend on the duration and intensity of precipitation, existing levels of flow arising from ablation at the onset of precipitation and whether any outburst of stored liquid water is released simultaneously from glaciers. Magnitudes of outburst-produced peak flows depend similarly on the level of background discharge arising from ablation and rainfall at the time of release as well as on the accumulated volume of water of stored and the drainage mechanism.

This paper has two aims. First, the impact of sustained heavy rain storms on runoff is examined for two adjacent highly glacierised Alpine basins, located at elevations for which data are generally unavailable. Impacts of outburst floods on runoff are also assessed, from an ice-dammed lake in one basin and associated with rainfall in the other. A conceptual model is used with the intention both to couple variables which influence the seasonal variability of the response of glacier runoff to precipitation, and to explain differences in runoff response in basins differing in proportion of glacier cover and altitudinal displacement.

BASIN CHARACTERISTICS

Effects of precipitation on glacier runoff have been examined for the months May through September in the years 1987 and 1993 at Findelengletscher and Gornergletscher, adjacent valley glaciers contiguous in accumulation areas. The two basins are nested within the upper Rhône basin, in the Pennine Alps, Kanton Wallis, Switzerland (Fig. 1). Characteristics of the basins and glaciers are given in Table 2.

Table 2. Characteristics of the basins containing Findelengletscher and Gornergletscher.

Basin	*Findelenbach*	*Gornera*
Glacier(s)	Findelengletscher Trifjigletscher	Gornergletscher
Basin area, km^2	24.9	82.0
Glacierisation, %	76.7	83.7
Basin elevation range, m a.s.l.	2500–4199	2005–4634

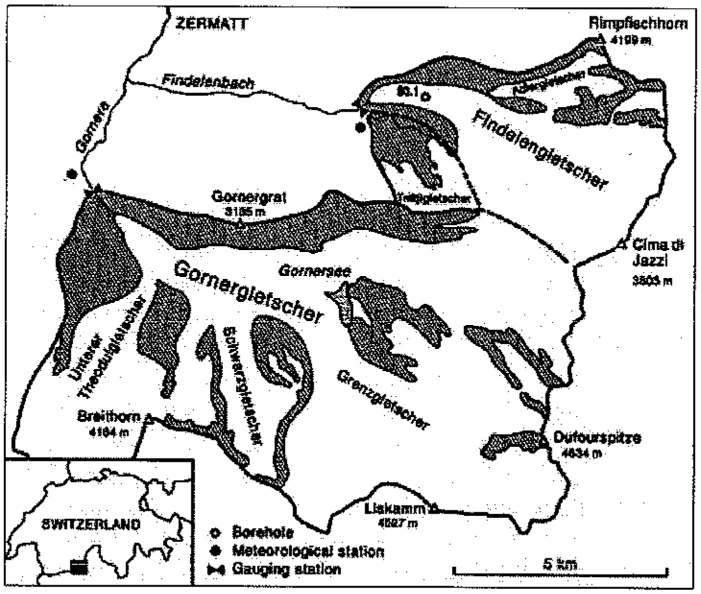

Figure 1. Map of the basins of the Findelenbach and Gornera showing gauging and meteorological stations, location of borehole 93.1 and the Gornersee.

An ice-dammed lake, Gornersee, forms in the apex of the junction between Grenzgletscher and Gornergletscher every spring, usually draining catastrophically under the ice once every summer. The stream draining from Trifjigletscher, prevented from reaching the tongue of Findelengletscher by the left lateral moraine, is captured by a hydroelectric adduction gallery which joins the Findelenbach immediately upstream of the gauge. Measured discharge is therefore the combined runoff from the basin containing both Findelengletscher and Trifjigletscher. Runoff from the two basins is gauged in rectangular flumes close to the termini of the glaciers. Precipitation and screened air temperature are recorded at a meteorological station adjacent to the gauge at Findelengletscher at an elevation of ~2510 m a.s.l.

PRECIPITATION, AIR TEMPERATURE AND RUNOFF FROM FINDELENGLETSCHER AND GORNERGLETSCHER

1987

Seasonal variation of energy input and discharge

Air temperature variations and daily total precipitation at Findelengletscher together with hydrographs for the Findelenbach and Gornera between 1 May and 9 October 1987 are shown in Figure 2. Air temperatures at elevations above Findelengletscher terminus were calculated assuming a constant lapse rate of 6°C km^{-1} (Barry 1992) and zero-degree isotherms for 3500 m and

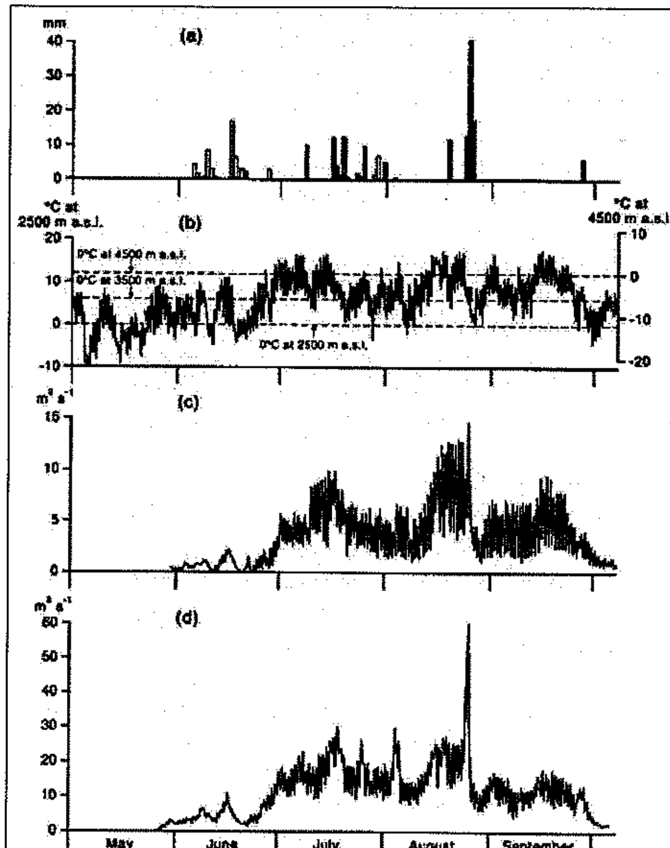

Figure 2. Daily total precipitation (a) and hourly mean air temperature measured at Findelengletscher meteorological station and calculated zero-degree isotherms at 3500 m and 4500 m a.s.l. (b), hourly mean discharge in the Findelenbach (c) and Gornera (d), for the period 1 May to 9 October 1987. The phase of precipitation falling above 3500 m is indicated as rain (solid) or snow (open columns).

4500 m, corresponding to +6° and +12°C respectively at 2500 m a.s.l., are also shown. The phase of precipitation at 3500 m, indicated in Figure 2 as liquid when air temperature at that elevation was calculated to be above 0°C or as solid when below, was determined from the Findelen temperature record and the lapse rate, and checked by field observation. Mean air temperature for the five months May through September 1987 was average, being ranked 9 in the 20-year record for 1970–1989, with near average precipitation, but June through September total runoff from Gornergletscher was ranked second highest (Collins 1991).

Energy inputs were unseasonably low during May, rising only after 20 June, with the glaciers remaining snow-covered until late June. Positive air temperatures were not sustained at elevations above 3500 m until almost the end of June. Until that time, melting of snow alone contributed to runoff of both Findelenbach and Gornera, periods of generally higher and lower levels of discharge reflecting periods of warm and cool weather respectively. Higher specific discharge from Gornergletscher resulted from warmer conditions and earlier exposure of ice at the lower elevations to which that basin extends. During several periods in June, new snowfall raised albedo, reduced melt and induced recession, snow covering all the Findelenbach basin for several days from 15 June. Once the area of exposed ice increased, underlying trends in discharge in both Findelenbach and Gornera moved roughly in parallel from July through September, broadly following the pattern of temperature fluctuation. The snowline ascended slowly in July, the rise from about 3000 m giving a particular boost to runoff from Findelengletscher in mid-July.

The highest daily discharge maxima of the season derived solely from melt accompanied very warm conditions from mid-August, unusually late in the season. Such annual maxima normally occur in late July or early August, a few days into a period of warm weather (e.g., Collins 1982, Röthlisberger and Lang 1987). High ablation rates are sustained by radiant energy inputs under persistent anticyclonic conditions and elevated sensible heat transfer from warm air. Underlying levels of discharge rise over several days as successive daily meltwater inputs to the internal drainage system are superimposed on receding flows which originated on previous days yet remaining in transit through the glacier. Increasing flows enlarge drainage pathways in ice, increasing hydraulic efficiency and allowing meltwater to drain more rapidly, so stabilising the level of discharge. Another exceptionally warm period, in mid-September 1987, resulted in further unseasonably high daily flow maxima. Absolute levels of discharge were lower than those produced in August, radiant energy input for melt being much reduced as the equinox approached.

Precipitation events

Rainfall first affected substantial areas of the two basins on 7 July, when 10 mm of rain fell at 2500 m, with presumably orographically enhanced quantities at elevations up to about 3500 m, above which there was snow. Runoff in the Findelenbach declined with the cooler conditions but the event produced the highest hourly average flow in the Gornera so far in the season. The next storm, from 15 July, again terminated a warm period, precipitation continuing until 19 July, in the form of rain at lower elevations despite falling temperature. 12.2 mm of rain produced the season-to-date maximum hourly discharge of 26 $m^3 s^{-1}$ in the Gornera at 18.00 h on 15 July, to be exceeded at the same time on 16 July, and reaching 30.0 $m^3 s^{-1}$ at 16.00 h on 17 July. These maxima were all timed close to the peak of the underlying thermally controlled diurnal runoff cycle. An outburst from a water pocket or release of water temporarily stored transit within Gornergletscher must have produced the peak on 17 July as only 1.2 mm of rain had fallen in the preceding 24 h. By 18 July, rain had turned to snow at elevations above about 3500 m and 12.2 mm of precipitation produced a daily maximum of only 23.8 $m^3 s^{-1}$. Daily maximum discharge in the Findelenbach during this storm period was raised only marginally, on 15 and 16 July, above the thermally related levels of the previous few days. This reflects both the smaller areal extent of the basin at lower elevations receiving rain by comparison with Gornergletscher, and the relatively high proportion of Findelengletscher catchment remaining snow-covered.

On 24 July, 9.8 mm of precipitation fell as rain to elevations well above 3500 m, raising discharge of the Gornera significantly above thermally related background levels, but again having little impact on the Findelenbach. 11.8 mm of rain on 18 August, after a warm period, with the freezing level rising above 4500 m (Fig. 2) increased daily total flow of the Gornera 16% above the thermally related levels of discharge of 17–19 August (0.292 × 106 m^3, equivalent to about 3.6 mm of rain uniformly distributed across the entire basin, assuming rapid return of runoff with no evaporation from all the catchment and no orographic variation in precipitation with elevation). As for the Findelenbach, the increase was 23% (0.16 × 106 m^3 or 6.4 mm of rain over the entire basin). This was a response to a rise of the transient snow line in the Findelengletscher basin, which greatly increased the snow-free area returning runoff rapidly and released some meltwater detained in the snowpack earlier in the season.

Torrential rainfall accompanied the storm which affected the basins between 23 and 25 August. Melt-produced discharge was already at an unusually high level, as described above, warm conditions having existed throughout the elevation range during preceding days. The 0°C isotherm stood between 3500 m and 4500 m a.s.l. over much of the region (Rey and Dayer 1990, Grebner and Richter 1991). Extensive areas of ice were exposed to melt, as a result of the interaction of the summer energy input with below average winter snow accumulation having taken the transient snowline to high elevation. Forty millimetres of rain was recorded at Findelengletscher (2510 m) between 0.00 and 16.00 h before the gauge became defective. Amounts of between 20 and 65 mm of precipitation were recorded that day at other gauges in the Pennine Alps to the west of Zermatt (Rey and Dayer 1990). Fifty-eight millimetres was recorded ~1 km downstream of the Gornera gauge (Collins 1998a). At Findelengletscher, this storm produced the highest continuous rainfall amount since the precipitation gauge was installed in 1970. Detailed analysis of the impact on runoff produced by the 23–25 August event is given by Collins (1998a). Peak discharge in the Gornera was greater in relation to background thermally produced meltwater discharge than that measured in the Findelenbach. More precipitation on 25 August, which occurred as snow at high elevation, made only a passing impact on runoff from both basins. A final rainfall event in the 1987 ablation season on 26 September produced only a minor impact on minimal runoff levels in both Gornera and Findelenbach, presumably surface runoff from rain being retained in the glaciers. In general, liquid precipitation raised runoff above thermally induced levels occurring before the storms, and maintained higher discharges during and for a period immediately after rainfall events.

Drainage of the Gornersee

Drainage of the Gornersee enhanced flow of the Gornera between 2 and 4 August, discharge increasing to a maximum of 29.7 m^3 s^{-1} by 16.00 h on 3 August. In many years, the outburst from the Gornersee provided the annual maximum instantaneous flow of the Gornera. The 1987 emptying was subdued by comparison with those delayed to August in other years. Peak discharge exceeded 60 m^3 s^{-1} in the late July–early August 1974 outburst for example (Collins 1986). In 1987, rain-induced floods from Gornergletscher twice exceeded the peak discharge attained during the drainage of the Gornersee.

1993

Seasonal variation of energy input and discharge

In 1993, runoff from both glaciers started to increase in late May, from which time diurnal fluctuations became evident. Whereas in 1987, air temperature at 4500 m first exceeded 0°C in late June, by the end of June 1993, the zero degree isotherm had exceeded that elevation during 4 episodes. From mid-June, discharge of the Gornera generally followed fluctuations of air temperature (Fig. 3). Drainage of the Gornersee from 19 June, superimposed on thermally induced rising flow, produced a maximum discharge of 29.7 m^3 s^{-1} in the morning of 22 June. 7.2 mm of rain on 21 June also contributed to the rising flow, followed by 18.6 mm overnight 22/23 June which briefly offset falling lake outflow. Discharge of the Findelenbach mimicked that of Gornera for much of the summer ablation period. Snowfall at higher elevations in the two basins from 9 July raised glacier surface albedo, and discharge from the two glaciers receded markedly for several days. From early August, though, for much of the month, the freezing level remained above 4000 m a.s.l., and, as in 1987, a wide expanse of bare ice was exposed to melt, discharge in the Gornera reaching a peak equal to the season-to-date maximum produced by the Gornersee outburst. Rainfall extending to high elevation added to the thermal maxima, sustaining flow on 24 August, when 16 mm fell at 2510 m a.s.l. at Findelengletscher. Flow in the Findelenbach sensitively followed energy input variations in August with a rainfall-enhanced season-to-date peak on 24 August as in the Gornera. Generally cool conditions with low flows from both glaciers then persisted until temperatures rose from 16 September, taking the freezing level back above 4000 m. This warm period culminated in a storm from 22 September which deposited 19 and 39 mm of rain on successive days in the Findelengletscher gauge. By the third day, rain had turned to snow down to 2000 m. Discharge in the Gornera peaked at 21.0 m^3 s^{-1} during the afternoon of 24 September, a level about one third of the August 1987 maximum despite considerably more rain. The Findelenbach gauge was rendered inoperational that afternoon by the deposition of sediment in the flume as sudden release of water backed up in the internal drainage system of Findelengletscher flushed sediment from the glacier sole (Barrett and Collins 1997).

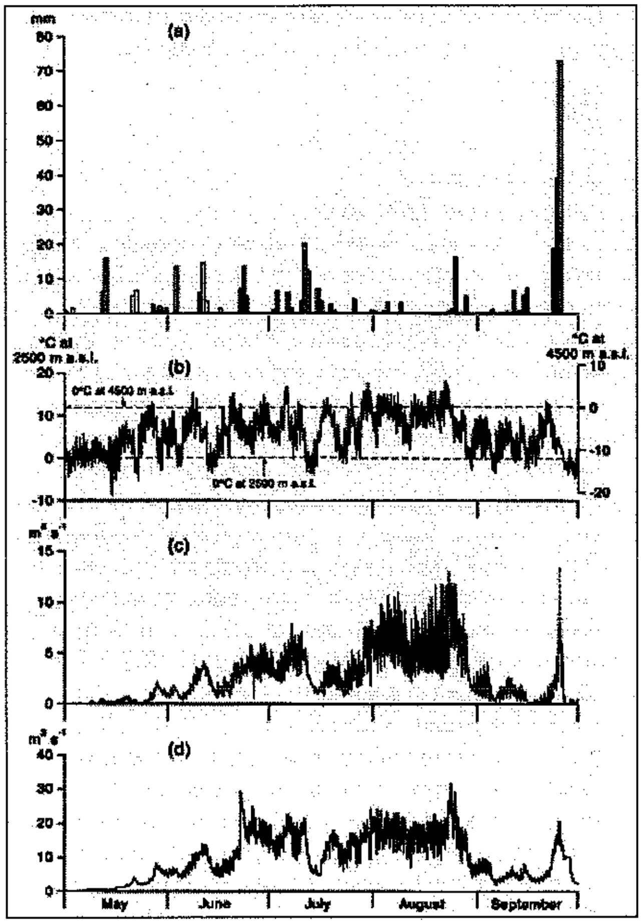

Figure 3. Daily total precipitation (a) and hourly mean air temperature (b) measured at Findelengletscher meteorological station with calculated zero-degree isotherm at 4500 m a.s.l., hourly mean discharge in the Findelenbach (c) and Gornera (d), for the period 1 May to 30 September 1993. Precipitation phase at 3500 m is indicated as rain (solid) or snow (open).

DISCUSSION

Factors influencing the seasonal pattern of runoff

The seasonal pattern of runoff from Alpine glacierised basins is dominated by the melting of snow and ice. Precipitation and energy inputs interact to determine both heat fluxes and surface energy balance which control overall melt rate. The nature of the substrate, snow or ice, influences energy balance through albedo. Once meltwater is produced, the type of substrate determines any delay in the concentration of runoff to drainage pathways. Timing of the rise of the transient snowline, and hence variation through time of the proportions of glacier and basin areas covered by snow, is therefore an important variable. Seasonal variation of energy-related components of runoff from a highly glacierised basin result from the interaction of hydrometeorological conditions, which vary with elevation, with the spatial (and altitudinal) evolution of the portions of the basin which are snow-covered and snow-free (i.e., consist of bare ice exposed to melting). In turn, the rise of the transient snowline relates to the interaction of winter snow accumulation with hydrometeorological conditions during the ablation season. The state of development of the internal drainage system of the glacier also has an influence on the pattern of runoff at seasonal and diurnal timescales. These conditions also influence seasonal variations in the response of runoff from glacierised basins to precipitation, and probably also affect timing and magnitude of lake and other outburst floods.

A conceptual framework for the interaction of these conditions (Collins 1995) is shown schematically in Figure 4. For a given energy input, thermal production of meltwater per unit area largely depends on the albedo of the snow/ice surface. Following removal of winter snow-cover by melt, albedo of a unit area of glacier surface falls from ~0.8 to ~0.4 as underlying ice becomes exposed, and specific melt rate is therefore increased by factor of between 2 and 3. How much runoff is produced in a day in the basin depends on the energy input and on the basin snow-covered area and the area of bare ice exposed to melt. Increasing runoff between June and early August effectively results from the rising transient snowline exposing an increasing area of bare ice to melt, enhanced melt rate per unit area of which more than offsets the loss of melt from the reducing area of snow on the glacier and in the ice-free part of the basin. Increasing area of bare ice together with rising sensible heat also help to offset the seasonal decline in radiation input after the solstice in June. The amplitude of the diurnal rhythm of meltwater flow widens as the bare ice area increases. As the season progresses, thinning of the snowpack and reduction of the horizontal distance to be traversed lessens the average time taken by meltwater to drain through snow. Increasing discharge also leads to improved efficiency of the glacier internal drainage network and hence to reduced meltwater transit times. The maximum elevation to which the transient snowline can rise late in the ablation season is reached at the altitude at which the amount of snow accumulated is just more than the cumulated seasonal energy input can melt. This position determines the maximum extent of bare ice, and leaves the basin lithosphere completely free of snow-cover.

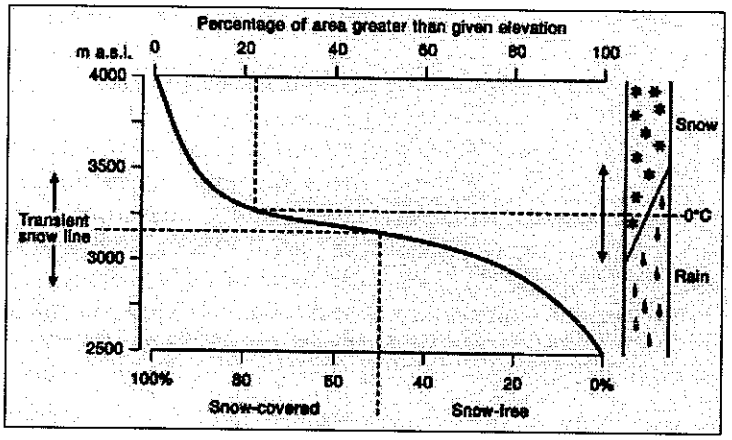

Figure 4. Schematic diagram showing how vertical movements of the transient snowline interact with Alpine basin hypsometry to determine the proportions of the basin area which are snow-free and snow-covered, and how the 0°C air temperature isotherm similarly interacts to partition basin area into portions over which precipitation falls as snow and rain.

The transient snowline falls when precipitation occurs as snow during summer. The position of the snowline at any time is thus a balance between amount of snow accumulated and energy receipt since the time of snowfall.

Conditions influencing seasonal variations in the response of runoff to precipitation

In alpine basins extending over considerable ranges of elevation, the intercept of the elevation of the zero-degree isotherm with the topography at the time of precipitation effectively partitions the catchment area into two zones, the higher receiving snow and, simultaneously, the lower rain (Fig. 4). The distribution of area by elevation (or the hypsometry) of a basin, alongside absolute elevation range, is thus critical in determining the partial areas of the catchment over which rain and snow will fall. Precipitation falling as snow has no immediate positive impact on runoff. Indeed, through raised albedo of the glacier surface, ice melt and runoff can be reduced for several days in summer months. The nature of the terrain type, snow, bare ice, moraine or rock, onto which liquid precipitation falls affects the response of runoff. Potential runoff from rain-on-snow, like that from water derived from surface snowmelt, is either retained in or delayed in transit through the snow depending on thermal conditions within the pack. Rain over bare ice runs off almost immediately into the subglacial drainage system as does meltwater from the fusion of surface ice. Again, rain falling on moraine-mantled bedrock runs off rapidly. Relative dimensions of snow-covered and snow-free partial areas of a glacierised basin therefore affect the response of runoff to liquid precipitation.

The framework shown in Figure 4 forms the basis of explanations of both the varying response of runoff from a glacierised basin to rainfall with progression of the ablation season, and differing responses of runoff from even adjacent basins to the same sequence of storms. Responses of runoff from Findelengletscher and Gornergletscher to precipitation in 1987 and 1993 reflected, however, not only seasonal increases in proportions and absolute areas of the two basins free of snow and the height of the zero-degree isotherm, but also meteorological conditions in the few days before each precipitation event. Such conditions determined the background thermally induced level of meltwater flow on which rain-derived runoff was superimposed. Variations in runoff response to the same storm between Findelenbach and Gornera reflect differing basin hypsometric curves (Fig. 5), differing overall elevation ranges (Table 2), and differing absolute distributions of area with elevation. If the transient snowline were to rise from 3000 to 3500 m a.s.l., the area returning runoff rapidly would increase from ~35 to ~70% (57 km^2) of the total basin area of Gornergletscher but from ~20 to ~80% (20 km^2) of Findelengletscher basin.

Timing of precipitation events and flood magnitudes

Had the precipitation delivered on 23–25 August, 1987, occurred one month earlier or two weeks later,

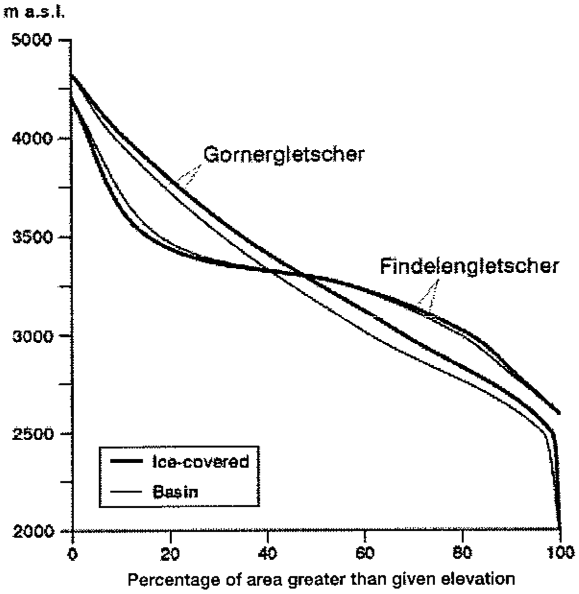

Figure 5. Hypsometric curves of Findelengletscher and Gornergletscher, and respective drainage basins.

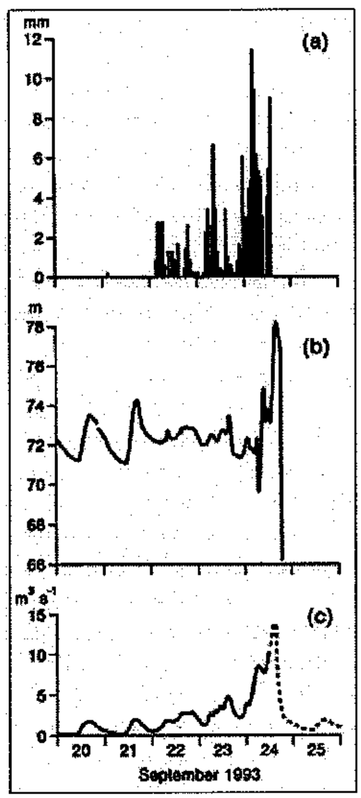

Figure 6. Hourly total rainfall at Findelengletscher meteorological station (a), water level above the subsole in borehole 93.1 (b), and discharge in the Findelenbach (c) between 20 and 25 September 1993.

responses of runoff to rainfall would have been quite different. In late July, the freezing level was lower and precipitation would have occurred as rain over an area 10–15% smaller than that over which rain actually fell in August. Snow-covered area would have been greater, and, together with lower thermally induced meltwater runoff, retention of a larger proportion of the smaller total amount of rain over the basin would have led to relatively subdued runoff peaks. By mid-September 1987, the zero-degree isotherm was also close to the 4000 m level reached in August, and the transient snowline was at least as high. The thermally produced background discharges were, however, much lower and so if the same storm had happened in September, resulting peak flood flows would have been smaller than those that actually occurred in late August.

Total liquid precipitation collected at the Findelengletscher gauge between 22 and 24 September 1993 exceeded that received during the August 1987 storm. The small underlying thermal component of runoff had however barely started to respond to the return of warm conditions. Whilst peak flood discharges were substantially higher than the general levels of flow preceding the storm, suppressed by the previous two weeks of September having been so cool, the September 1993 peak in the Gornera was much lower than that resulting from less rain in August 1987.

Capacity of the glacier internal drainage system

Additionally, by September, capacity of the glacier internal drainage system becomes reduced, basal drainage pathways closing under ice overburden pressure as discharge declines. Similarly, in spring and early summer, after minimal winter discharge, the capacity of the drainage system will be low. Input of a large volume of runoff from sustained rain on the ice forming the glacier surface may lead to inflow exceeding discharge through the internal drainage system and hence to temporary storage of water and high basal water pressure. A sudden outburst might then be triggered. A borehole (93.1) drilled to the subsole of Findelengletscher about 1.5 km from the terminus remained instrumented through the September 1993 storm (Fig. 1). A pressure transmitter was suspended 66.2 m above the base of the 160 m deep hole and water level was recorded every 10 min. Borehole water level and discharge varied in parallel on 20 and 21 September (Fig. 6). Once the rain had started, water level and discharge in the Findelenbach responded to bursts of rainfall. After several cycles of rising water level followed by abrupt falls over a range of several metres, water level rose to a maximum of 78.08 m above the base of the hole on 24 September. Water level then suddenly fell beneath the level of the pressure transmitter and remained there until observations ceased on 1 October. About 104 t of sediment was evacuated from the glacier subsole in the flood as the drainage system enlarged releasing the backed-up water. A more detailed analysis is given by Barrett and Collins (1997). Fluctuations in the discharge of the Arve during the rain-induced flood of 24–26 July 1996 suggest similar backing-up and emptying of water pockets beneath both the glacier d'Argentière and Mer de Glace (Chaverot and George 1998).

CONCLUSION

The transient snowline has a critical role in the hydrology of Alpine glacierised basins in separating partial areas which are either snow-free and return both rain and meltwater as runoff rapidly or snow-covered in which rain and melt percolate into snow to be delayed in transit or retained, according to thermal conditions in the pack. With respect to storm rainfall, the position of the transient snowline interacts with basin hypsometry to define the actual area of the portion of the basin that will rapidly form runoff. Elevation of the zero-degree Celsius isotherm also interacts with basin hypsometry to determine the area of catchment over which precipitation will fall as rain. The quantity of water contributing to rain-induced augmentation of flow is related to the amount of rain falling during a storm and to the partial area of basin which is both snow-free and receiving liquid precipitation. Additionally, precipitation amount normally increasing with elevation also influences runoff, the effect being greater the higher the transient snowline and the larger the snow-free catchment area and the higher the freezing level in the atmosphere. Glacierised basins exhibit differing responses to rainfall because of differences in both hypsometry and absolute elevation range.

Whilst the quantity of moisture delivered by a storm is a prime determinant of the runoff response, the timing of a storm in relation to the steady seasonal progression of the rise of the transient snowline and the more volatile episodic rising and falling of the freezing level during the ablation season is also critical in Alpine glacierised basins. The snowline is likely to reach maximum elevation and the snow-free area become largest in the period between mid-August and mid-September. Delivery of a large quantity of precipitation in that window is likely therefore to be in the form of rain over an expanded non-retentive basin surface. The thermal component of runoff is likely to be highest in late July and August, so that sustained heavy rainfall in that period is most likely to produce peak flows, especially following a period of elevated air temperatures. In warm summers after winters in which snow accumulation is below average, transient snowline and freezing level will rise sooner and higher, and extend forward the window of risk. In such warm summers, a given rainfall event might be expected to produce higher magnitude runoff.

Hydrological conditions within glaciers at the time of storm impact also influence the magnitude of rain-induced floods from glacierised basins. Rain over glaciers at times when the capacity of the internal hydrological system to discharge water supplied from the ice surface is low, early in the season before the drainage system expands or in late summer when ice overburden pressure has closed conduits under recession flow conditions, may lead to temporary storage of water and high subglacial water pressure. Runoff from rainfall might then trigger a sudden outburst, as appears to have been the case at Findelengletscher in September 1993 and at glaciers in the Arve basin in July 1996.

Sustained heavy rainfall events, with liquid precipitation extending to elevations as high as 4500 m a.s.l., produce major floods from glacierised basins in the Alps. As a result of the other factors influencing runoff, the relationship between the amount of rain and the magnitude of runoff is not simple. Outbursts from the ice-dammed Gornersee can be equalled and surpassed as the annual peak runoff event in the Gornera in summers which are both warm and stormy. Attempts to monitor or forecast floods from glacierised alpine basins will require frequently updated information concerning building up of lake levels, elevation of the transient snowline and snow-covered area, continuous air temperature measurement at high altitude stations, continuous monitoring of water storage in glaciers, using water levels in boreholes, as well as close-interval measurement of rainfall intensity at high elevation sites. Site-specific knowledge of the nature and behaviour of glacier internal drainage systems may be critical for flood forecasting purposes.

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