Internationales Symposion
INTERPRAEVENT 1996 – GARMISCH-PARTENKIRCHEN
Tagungspublikation, Band 1, Seite 65 – 74

GLACIAL DISCHARGE AS AFFECTED BY CLIMATE CHANGE

AUSWIRKUNGEN VON KLIMAÄNDERUNGEN AUF DEN ABFLUSS VERGLETSCHERTER GEBIETE

L. N. BRAUN & H. ESCHER-VETTER

Abstract

Climatically induced changes in glacier mass balance and glacier discharge are discussed using the time series of Aletsch Glacier, Switzerland, starting in 1900, and of Vernagtferner, Austria, where mass balance measurements began in 1964. For the Aletsch Glacier basin (glacierization approx. 66%) drained by the Massa River, there is no obvious trend in the annual and maximal discharges despite heavy mass losses, which led to a diminishment of the glacierized areas by one-third over the total alpine region since the beginning of this century. Over the past 20 years, however, mean yearly and maximal discharges of Vernagtbach (Oetztal Alps, basin glacierization 80%) have doubled as a result of strongly negative glacier mass balances in recent years. If these glacier mass losses continue, a higher flood potential in heavily glacierized basins must be expected, particularly if high intensity rainfall events coincide with melt peaks.

Zusammenfassung

Klimatologisch bedingte Schwankungen im Gletschermassenhaushalt und Gletscherabfluss werden anhand von Zeitreihen des Aletsch Gletschers (Schweizer Alpen), beginnend 1900, und des Vernagtferners (Ötztal, Österreich) seit 1964 diskutiert. Trotz des markanten Gletscherschwunds, welcher im gesamten Alpenraum seit Beginn dieses Jahrhunderts zu einer Verminderung der vergletscherten Fläche um ca. ein Drittel führte, kann man im Jahresabfluss und in den jährlichen Maxima des Abflusses der Massa keinen offensichtlichen Trend beobachten. Jedoch haben sich im Verlaufe der vergangenen 20 Jahre die Jahresabflüsse des Vernagtferners

in etwa verdoppelt. Parallel dazu sind die Tagesamplituden der Schmelzwasserabflüsse stark angestiegen, was vor allem auf das starke Schrumpfen der Firn- und Schneeflächen des Gletschers zurückzuführen ist. Falls die Massenverluste der Gletscher in den kommenden Jahren anhalten sollten, muss im hochalpinen Raum mit einer Verschärfung der Hochwassergefahr gerechnet werden, insbesondere in Situationen, wo Schmelzwasserspitzen und Starkniederschläge zusammenfallen. Sollten jedoch kühle und feuchte Sommer wie z.B. 1995 nicht nur eine Ausnahme der Regel sein, dann besteht Hoffnung, dass uns auch in Zukunft die Gletscher und nachhaltige Glazialabflüsse erhalten bleiben.

Introduction

Discharge originating from the melting of glaciers displays various differing behaviours. On one hand, it maintains high flows during the melt season in dry regions or in years with small precipitation amounts. On the other hand, floods caused by glacial discharge have long been a serious threat in high-alpine areas. As an example, outburst floods from the two glacial-dammed lakes "Rofener" and "Gurgler Eissee", both in the Oetztal valley, Austria (location see **Figure 1**), are well documented since the end of the 16th century. Leys and Reinwarth (1975) gave a first overview of the possible influences of glaciers in causing floods and ice avalanches, and presented guidelines for torrent and avalanche control. Röthlisberger and Lang (1987) thoroughly discuss the characteristics of

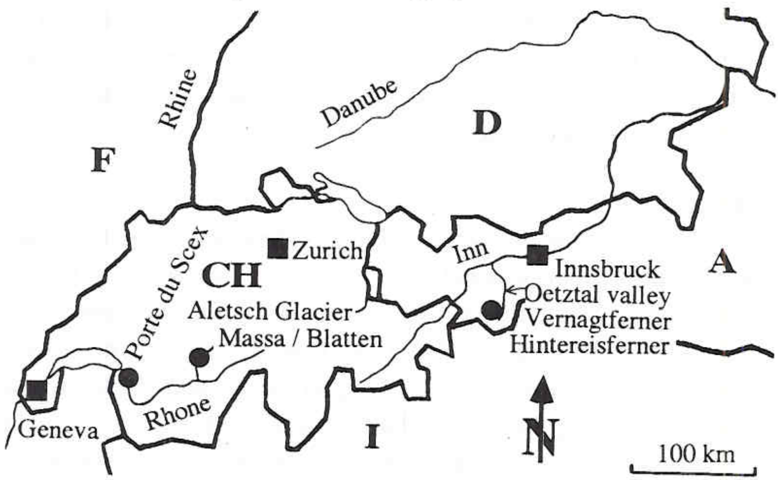

Figure 1 Location map of selected sites discussed in the text.

glacier runoff such as the compensating effect of glaciers, the storage processes controlling periodic and aperiodic variations, and the causes of extreme floods. The influence of long-term changes in glacierization and their impact on water resources management were treated in detail by Kasser (1973, 1978), and more recently by Chen and Ohmura (1990), and Chen (1991). These contributions showed that summer discharge of the Rhone River near its inflow to Lake Geneva (Porte du Scex, current glacierization 14%) is reduced by about 70 mm a^{-1} or 8% due to the observed reduction of glacierized area (165 km^2 or 19%) between 1916 and 1968. Possible effects of climatic changes on glacial melt and flood potential in alpine regions are discussed by Braun (1996) for example, and this topic also has received increased attention in the press (see for example Hoelzgen, 1995).

Long-term variation of glacier mass balance and discharge of Aletsch Glacier, Switzerland

The general reduction in glaciation in the course of this century and its effect on discharge can be well demonstrated by the cumulative values of the glacier mass balance of Aletsch Glacier and the annual discharge of the Massa / Blatten (see **Figure 2**). The most significant mass losses occurred in the 1940s resulting in strongly increased runoff values, and also the years after 1985 show a consistent sequence of above-normal discharge values. If one considers the complete discharge series as a whole, however, no clear trend can be discerned. This also holds for the yearly maximal discharges of the Massa (Spreafico and Aschwanden, 1991). Maximal discharge values of about 127 $m^3\ s^{-1}$ occurred in 1928 and 1939, corresponding to a specific value of about 920 $l\ s^{-1}\ km^{-2}$ (with respect to a glacierized area of 138 km^2), and a value of 105 m^3/s in 1971 (corresponding to 854 $l\ s^{-1}\ km^{-2}$ at a glacierized area of 123 km^2, see also Röthlisberger and Lang, 1987).

Kuhn (1990) has demonstrated how the climatic variables such as snow accumulation, air temperature, water vapour pressure, wind speed and radiation influence the mass balance of glaciers, which in turn is strongly linked to the altitude of the equilibrium line (ELA) at the end of the ablation season, and to discharge. According to his analysis covering data from Hintereisferner (location see **Figure 1**) since the early 1950s,

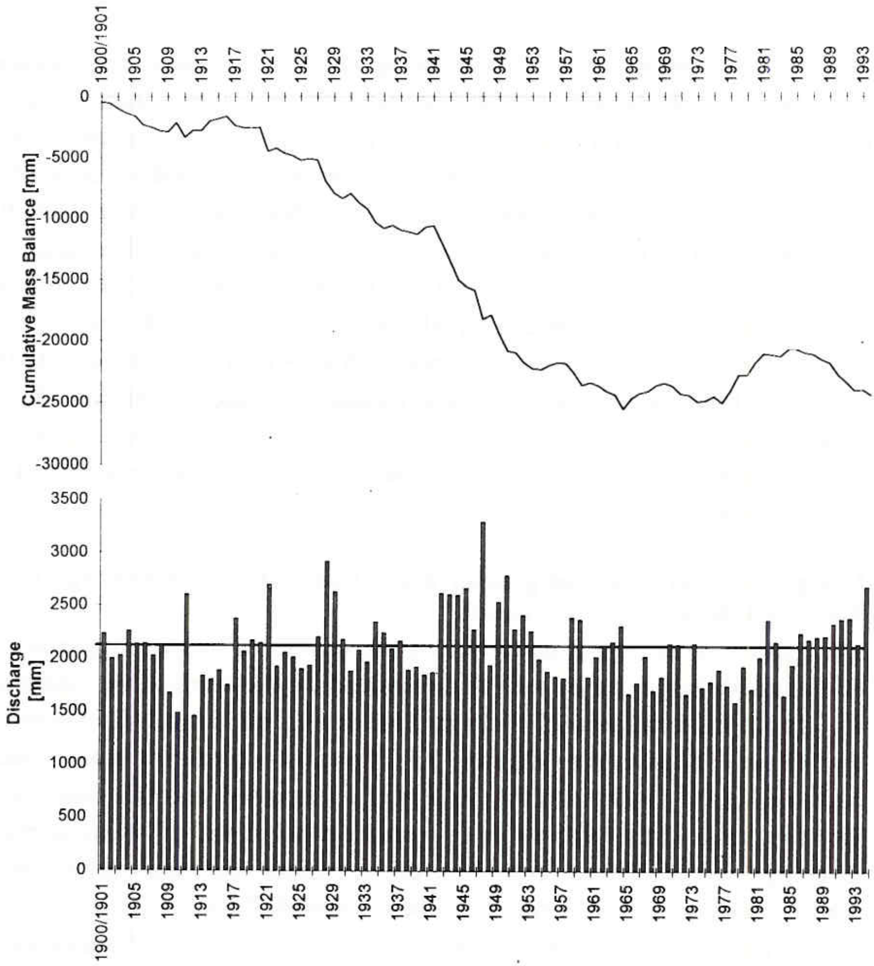

Figure 2 Cumulative mass balance of Aletsch Glacier (derived from the hydrological method) and annual discharge of the Massa River / Blatten, 1900/01 to 1993/94. Data based on Müller et al. (1995) and M. Aellen (personal communication).

changes in ELA can be well expressed as a function of air temperature change, which is commonly used as a measure of climate change. Kuhn arrives at a value of 170 m elevation change in equilibrium line altitude due to a change in air temperature of 1 °C.

Annual discharge from glacierized basins can be expressed in its turn as a function of equilibrium line altitude and yearly precipitation as shown by Kasser (1978). In **Figure 3**, discharge of the Massa River draining Aletsch Glacier is given for the hydrological years 1930/31 to 1977/78 as a function of equilibrium line altitude and annual precipitation. According to this graph, total discharge is the sum of discharge from precipitation of the individual year (snowmelt and rain) and discharge from icemelt. Two extreme hydrological years are 1977/78 with a strongly positive mass balance (+ 1800 mm) and low runoff, where over 80% originated from precipitation of that year and only 20% from melting of glacier ice, and the year 1946/47 showing a strongly negative mass balance (-2400 mm), where only 40% of the very high runoff value came from precipitation of that year and some 60% from icemelt. This diagram can also be used to derive discharge amounts at Aletsch Glacier under changed precipitation and air temperature conditions, the latter being parameterized by equilibrium line altitude.

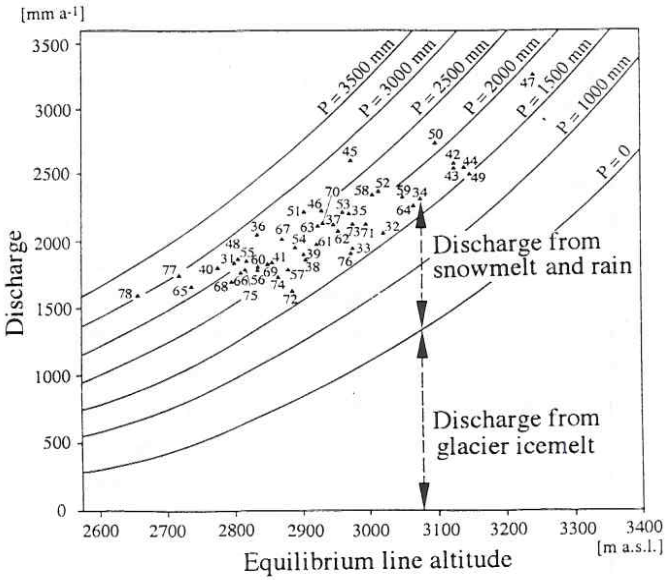

Figure 3 Annual discharge of the Massa River at Blatten, draining Aletsch Glacier, 1930/31 to 1977/78, shown as a function of equilibrium line altitude and annual precipitation P. Figure redrawn after Kasser (1978).

Glacier mass balance and discharge from Vernagtferner

Figure 4 shows the cumulative values of the glacier mass balance of Vernagtferner since 1964/65. After a period of 17 years characterized by generally balanced budgets, consistent mass losses have been occurring since the early 1980s.

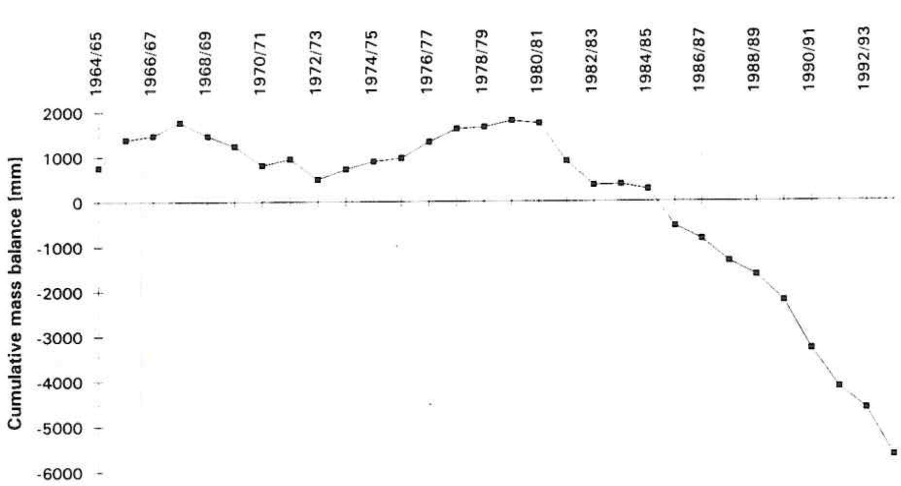

Figure 4 Cumulative mass balance (determined by the direct glaciological method) of Vernagtferner, Oetztal Alps, since 1964/65.

As a consequence of these mass losses at Vernagtferner, a clear trend towards higher annual and maximal discharge can be observed for Vernagtbach, draining the basin of Vernagtferner (Oetztal Alps, Austria, basin area = 11.4 km^2, see **Figure 5**, Escher-Vetter and Reinwarth, 1995). Mean annual discharge, which has been recorded at the site since 1974, has almost doubled, and maximal discharge was usually higher than 900 $l\ s^{-1}\ km^{-2}$ (mean hourly specific value in respect to the glacierized area of 9.1 km^2 or 79% in 1990) during the past 10 years. An exceptionally high specific discharge of over 1600 $l\ s^{-1}\ km^{-2}$ was observed in August 1994 (H. Behrens, personal communication), when the gauging station was damaged, and the first significant data loss occurred since the beginning of measurement (see also **Figure 6**).

Oerter and Reinwarth (1988) gave a first analysis of the dominant runoff mechanisms by relating the annual maximal discharges of Vernagtbach to melt or rainfall events. On 1 August 1983 the maximal melt-induced peak discharge of 8.3 $m^3\ s^{-1}$, corresponding to 885 $l\ s^{-1}\ km^{-2}$ (specific value with respect to glacierized area of 9.35 km^2 or 82%) was observed, and on 24 August 1987 the highest rainfall-induced peak of 9.35 $m^3\ s^{-1}$, corresponding to 817 $l\ s^{-1}\ km^{-2}$ (specific value with respect to total basin

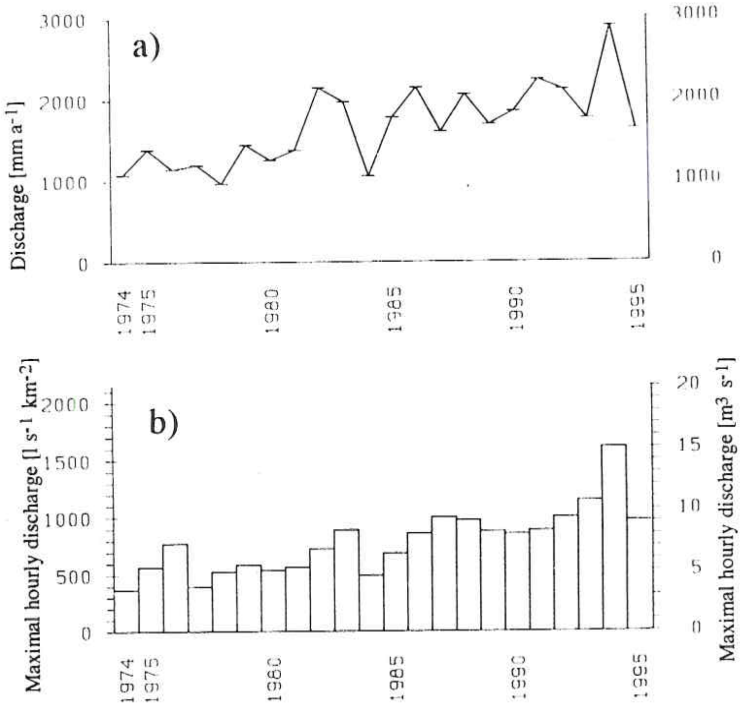

Figure 5 Discharge of Vernagtbach, Oetztal Alps, 1974 - 1995, a) annual and b) maximal hourly discharge (specific value related to the mean glacierized area of 9.3 km^2) .

area or 1020 l s^{-1} km^{-2} with respect to glacierized area). Escher-Vetter and Reinwarth (1994) extended the analysis to the data until 1993 using mean daily maxima of discharge. They demonstrated that the melt-induced portion of glacial runoff has become more significant in the past few years. This is related to the succession of strongly negative mass balances since 1982 resulting in an ever-increasing portion of bare ice and the decreased size of the firn area of Vernagtferner, showing a minimal extent of about 10% of the glacierized area at the end of the 1994 ablation season. These dramatically changed runoff conditions can be further exemplified by the diurnal variation of discharge typical for the early 1980s and the 1990s (see **Figure 6**). Under balanced mass budget conditions the extent of the firn area is about 70% of the total glacier area, and meltwater runoff is delayed for days through percolation in the firn and intra-glacial storage (for more details concerning meltwater pathways and storages see Oerter et al., 1981). As a result, diurnal fluctuations of discharge are rather small and peak runoff in the order of

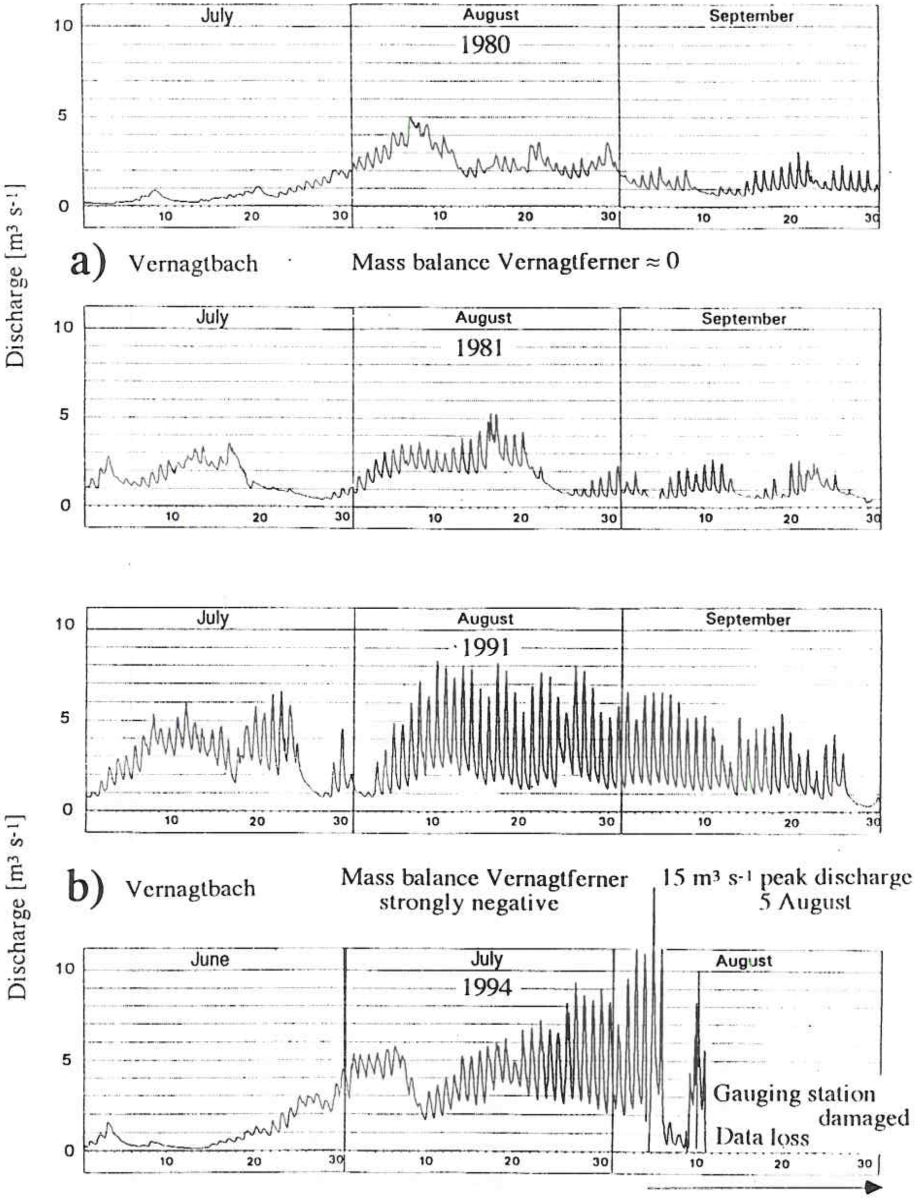

Figure 6 Diurnal fluctuations of discharge of Vernagtbach, typical for a) balanced mass budget of Vernagtferner, and b) after a sequence of strongly negative mass balances.

5 m^3 s^{-1}. The examples of the summers of 1991 and 1994 show that melt runoff from the bare ice surfaces with typical travel times of a few hours becomes much more dominant, and peak discharge values of over 10 m^3 s^{-1} and rather low values at night are observed. Because of these altered runoff conditions the upstream section of the gauging station had to be revised to increase its throughflow capacity.

Conclusions

In this century, glaciers have shown a wide range of reactions to the observed climatic conditions. As a consequence of highly negative mass balances, maximal discharges occurred in years characterized by below-normal precipitation and high summer air temperatures. A sequence of such years is able to reduce the firn reserve of glaciers to such an extent that an increased flood potential in high alpine regions must be expected, particularly if peak melt rates occur simultaneously with heavy rainfalls.

Future climatic trends may involve a general warming, possibly coupled with a change in precipitation amounts and distribution. If these trends lead to a climatic state of continuous series of dry, warm summers, the drastic glacier mass losses should continue in the future. If, however, a cool and rainy spring and early summer like that of 1995 should begin to occur more frequently, glaciers and glacier discharge are likely to remain for generations to come.

References

Braun, L.N., 1996: Gletscherabflüsse unter verschiedenen klimatischen Bedingungen. Tagungsband des Internationalen Symposiums "Klimaänderung und Wasserwirtschaft", 27./28. Nov. 1995, München. Hefte des Institutes für Wasserwesen, Universität der Bundeswehr, München, im Druck.

Chen, J.,1991: Changes of Alpine Climate and Glacier Water Resources. Zürcher Geographische Schriften, Heft 46, Geographisches Inst. ETH Zürich, 196 p.

Chen, J. and Ohmura, A., 1990: Estimation of Alpine glacier water resources and their change since the 1870s. IAHS Publ. no. 193, 127-135.

Escher-Vetter, H. und Reinwarth, O., 1994: Untersuchungen zum Niederschlag- und Abflussverhalten eines stark vergletscherten Einzugsgebietes in den Oetztaler Alpen. Annalen der Meteorologie, 30, Deutscher Wetterdienst, Offenbach, 307-310.

Escher-Vetter, H. and Reinwarth, O., 1995: Two decades of runoff measurements (1974 to 1993) at the Pegelstation Vernagtbach/ Oetztal Alps. Zs. Gletscherk. und Glazialgeol., 30, 53-98.

Hoelzgen, J., 1995: Mahlstrom im toten Eis. Der Spiegel, 42/1995, 196-206.

Kasser, P.,1973: Influence of changes in the glacierized area on summer runoff in the Porte du Scex drainage basin of the Rhône. AIHS (IAHS) Publ. no. 95, 219-225.

Kasser, P.,1978: Rezente Gletscherveränderungen in den Schweizer Alpen. Jahrbuch der Schweizer Naturforschenden Gesellschaft, wissenschaftl. Teil, 106-138.

Kuhn, M., 1990: Energieaustausch Atmosphäre - Schnee und Eis. Mitteilungen der VAW, Nr. 108, Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie, ETH Zürich, 21-32.

Leys, E. und Reinwarth, O., 1975: Auswirkungen der Gletscher und der Gletscherabflüsse auf die Wildbach- und Lawinengefahr und ihre Berück-sichtigung in den Gefahrenzonenplänen. Interpraevent 1975, 345-357.

Müller-Lemans, H., Funk, M., Aellen, M. und Kappenberger, G., 1995: Langjährige Massenbilanzreihen von Gletschern in der Schweiz. Zs. Gletscherk. und Glazialgeol., 30, 141-160.

Oerter, H., Baker, D., Moser, H. and Reinwarth, O., 1981: Glacial-hydrological investigations at the Vernagtferner Glacier as a basis for discharge model. Nordic Hydrology, 12, 335-348.

Oerter, H. und Reinwarth, O., 1988: Beobachtungen zum Hochwasserabfluss von einem Alpengletscher (Vernagtferner, Oetztaler Alpen). Mitteilungen der VAW, Nr. 94, Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie, ETH Zürich, 241-256.

Röthlisberger, H. and Lang, H., 1987: Glacial Hydrology. In: Gurnell, A.M. and Clark, M.J. (Editors), Glacio-fluvial Sediment Transfer, An Alpine Perspective. John Wiley & Sons Ltd., 207-283.

Spreafico, M. und Aschwanden, H., 1991: Hochwasserabflüsse in schweizerischen Gewässern. Mitteilungen der Landeshydrologie und -geologie, No. 17, Bd. IV (Reuss, Limmat, Rhone, Tessin, Adda, Inn), Bern.

Address of authors:

Dr. Ludwig N. Braun & Dr. Heidi Escher-Vetter

Bayerische Akademie der Wissenschaften, Kommission für Glaziologie

Marstallplatz 8, D-80539 München

Tel. 089 230 31 195, Fax: 089 230 31 100