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FREQUENCY AND CHARACTERISTICS OF GLACIER FLOODS IN THE SWISS ALPS

by

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ABSTRACT

Damage due to glacier floods in the Swiss Alps occurs about once every two years at present, despite the pronounced retreat of glaciers during the twentieth century and the installation of many water reservoirs, which act as flood retention basins. Over half (60 to 70%) of the observed floods are caused by outbursts of marginal glacier lakes or sudden breaks of ice dams, and 30 to 40% by ruptures of water pockets. In a glacierized mountain region as densely populated as the Swiss Alps, even debris flows triggered by outbursts of very small water masses may be dangerous. Historical information about glacier floods in the Swiss Alps, although incomplete and heterogeneous, is used as an empirical basis for an attempt to recognize potential hazards at an early stage by considering outburst processes, volumes of water involved, potential peak-discharge values, lithology and inclination within the reach of glacier streams.

INTRODUCTION

During historical times, glacier floods have repeatedly caused regional catastrophes in the Swiss Alps. In many cases the situation has become less dangerous due to the pronounced retreat of the glaciers during the twentieth century. Also many glacierized catchment areas have seen the building of reservoirs which act as flood retention basins during the summer. Nevertheless, glacier floods still cause damage regularly. Many Alpine villages lie outside the former regional area of danger from the main stream of the valley, but they are situated on the active alluvial fans of tributaries of this main stream and are consequently exposed to the local danger of flooding from the tributary valleys (Röthlisberger 1981). Furthermore, the rapidly advancing development of tourism in high Alpine valleys brings more and more human beings and installations into zones of potential danger that were previously avoided. The frequency of events causing damage seems to be on the increase rather than the decrease (Haeberli 1981). Alpine reservoirs which are being converted to operate on pump storage in connection with the extension of nuclear power production, and also reservoirs which operate on a weekly basis, raise the question of potential peak-discharge values from glacierized areas, and thereby that of the capacity of the flood-release structures and the height of the "freeboard".

In connection with known risks of flooding in glacierized areas, relatively broad experiences already exist in the realm of protective measures to be met, observation and prognosis (e.g. Röthlisberger 1979, Haeberli 1981). When the question is one of recognizing and estimating possible incidents of damage at an early stage, a noticeable gap is encountered. Since glacial and periglacial processes, within the framework of the permanent climatically-dependent glacier fluctuations in the Alps, usually lead to the build-up of a recognisably dangerous situation over a time span of years or decades, it is reasonable to observe and to judge the development of glacial lakes over a long period of time. Theoretical considerations do not take into account the variety of events as they are observed in nature and therefore risks of flooding in glacierized areas have to be estimated on the empirical basis of historical information. The Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie, Eidgenössischen Technische Hochschule Zürich (VAW/ETHZ), has compiled documentation about historical incidents of glacier floods. On the basis of this, the frequency and characteristics of such incidents are discussed briefly here, and deductions made about some simple criteria which are applicable in practice for the estimation of peak-discharge values and potential danger zones. These criteria are used to make an approximate estimate of the risk by considering the worst possible case. More sophisticated methods and techniques can then be applied in critical cases to predict and avoid flood damage after this first examination (cf. Clarke 1982).

FREQUENCY AND CHARACTERISTICS OF GLACIER FLOODS

More than 100 unusual (non-periodic) glacier floods have been observed in the Swiss Alps since the beginning of the Little Ice Age. The expression "unusual" points to the fact that it is impossible to define the limits of the term "glacier floods" objectively. Events discussed here are those which the population at the time considered important enough to record in writing and which were reported more or less without contradiction. Annual events, such as the bursting of the Gornersee, are not included in this number. Due to the fact that multiple repetition of events occurred in several cases (e.g. Aletschgletscher at Märjelensee, Allalingletscher at Mattmarksee, Glacier de Giétro at Lac de Mauvoisin), less than 40 glaciers, or ~2 to 3% of all Swiss glaciers, are involved. Even though the cases displaying the most frequent repetition have now been made safe by the construction of dams in connection with power production, the frequency of events causing

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damage has increased in the last few decades. To date, almost 200 people have lost their lives because of glacier floods. This represents, on average, less than one death per year and illustrates the moderate importance of the problem when taken as a whole, compared to other dangers, both natural and man-made. In a particular case, however, mountain communities can still, even today, be faced with difficult economic problems as a result of a glacier flood. In many cases, it is indeed known that an event has taken place, but quantitative information, because of the nature of the incident, is very rare. For example, discharge values had often to be estimated approximately, since suitable gauging stations were either non-existent or destroyed in the flood. In addition, the measured discharge values are sometimes doubtful because the cross-sectional flow has, in many instances, been changed during the flood by erosion and sedimentation processes.

Over half (60 to 70%) of the observed floods were caused by outbursts of marginal glacier lakes or sudden breaks of ice dams, and 30 to 40% by ruptures of water pockets located within the glacier. In each of the following cases, Aletschgletscher at Märjelensee (23 events), Grubengletscher in Canton Bern (several events) and Glacier d'Otemma (five events), a side valley was dammed by a glacier in the main valley. Bursts of glacial lakes in the main valley tend to be repetitive also. These glacial lakes are dammed by glaciers from the side valleys (e.g. Allalingletscher at Mattmarksee: 23 events). The existence of high and steep steps from hanging valleys presents the additional danger of damming by the debris from ice avalanches in such cases. The rupture of such a dam can lead to exceptionally high discharge peaks (e.g. Glacier de Giétro at Lac de Mauvoisin: five events). Outbursts from proglacial lakes in the forefield of the glacier (e.g. Vadret da Roseg, Steingletscher) and from periglacial lakes (thermokarst in permafrost, e.g. Rottalgletscher in Canton Wallis) appear to be non-repetitive. The Gornersee, which bursts annually, is dammed between two glacier tongues which flow together, whilst the subglacial lake under the tongue of Glacier de Ferpècle represents a borderline case between a lake burst and a water-pocket rupture. Water-pocket ruptures are particularly unpleasant since such events cannot be predicted from the present state of knowledge of the subject. As Table I shows, glaciers with known water-pocket ruptures are relatively steep, but there do not seem to be any simple, discernible, morphological characteristics which make such glaciers recognisable. Maritime temperate glaciers with mean annual air temperature at the equilibrium line T_E (cf. Kuhn 1980, Haeberli 1982) >-3°C (e.g. Stammbachgletscher, T_E = -2.5°C) and continental, partially cold glaciers with T_E <-3°C (e.g. Hohberggletscher, T_E = -7.5°C), small (e.g. Plan Névé: 0.52 km^2) as well as relatively large Alpine glaciers (e.g. Findelgletscher: 19.09 km^2) are included in this list of problem glaciers. The fact that the famous water pocket on Glacier de Trient frequently ruptures exactly above the steep area of the glacier tongue makes even the characteristic of the steep slope somewhat relative. The lack of clarity in the term "water pocket" illustrates perfectly the dilemma of the glaciologist who is faced with a situation which he does not fully understand.

The spatial distribution of known events is shown in Figure 1. The concentration in the southern valleys of Canton Wallis is striking, and shows that naturally-occurring lake bursts are associated with valley glaciers and water-pocket ruptures with steep hanging glaciers. However, there is not, as yet, an obvious reason for the fact that glacier floods occur much more frequently in the Swiss part of the Mont Blanc group, in Saastal and Mattertal, than in the Berner Alpen or the Bernina group. In general, areas prone to glacier floods lie outside the traditional hazard zones of mountain torrents, described by Zeller (1972). Only few glacier floods are, therefore, also directly associated with heavy precipitation. With the exception of two events (a harmless water-pocket rupture on Festigletscher in February 1967 and an outburst of the Märjelensee (Aletschgletscher) in January 1883), all dated events fall within the months of June to October (Fig.2). Glacier floods occur most frequently in the months of June, July and August, after the onset of snow-melt and probably during the time in which the outflow channels, which

TABLE I. MORPHOLOGICAL CHARACTERISTICS OF GLACIERS WITH KNOWN WATER-POCKET RUPTURES IN THE SWISS ALPS

Year	Glacier	Process	Actual glacier surface area (km^2)	Mean inclination of glacier surface (°)	Change of inclination along long profile of glacier surface	Mean annual air temperature at the equilibrium line T_E (°C)	Area of intense crevassing
1828	Bider	?	1.4	25	convex	-6	ablation area
1899	Crête-Sêche	?	1.1	25	concave	-3.5	-
1899,1967	Festi	?	2.2	15	steps	-7	steps (ice falls)
1943	Findelen	sudden break	19.1	10	steps	-6	steps
1930	Grands	?	2.0	25	convex	-4	lower part
1776,1842,1951	Unter Grindelwald	sudden breaks	21.7	18	complicated, steps	-2.5	steps (ice falls)
1898,1926,1966	Hohberg	?	3.6	25	convex/steps	-7.5	ablation area
1978	Kin	?	2.8	20	convex/steps	-6.5	ablation area
1898	l'A Neuve	sudden break?	4.1	15	convex/steps	-3	steps
1920	Maelliga	?	0.6	20	concave	-6	-
1920,1928	Orny	?	1.5	12.5	uniform	-4	-
repeatedly	Plan Névé	?	0.5	25	weak steps	-1.5	-
1900,1934,1947	Rhone	sudden break	17.4	7.5	steps	-3	steps (ice falls)
repeatedly	Trient	progressive enlargement?	6.6	20	convex	-4	ablation area
repeatedly	Saleinaz	sudden breaks?	5.0	15	weak steps	-4.5	steps
1945,1976	Stammbach	sudden break in 1945	0.8	30	weak steps	-2.5	steps
1899	Zmutt	?	17.0	12.5	concave/steps	-4.5	steps

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Fig.1. Spatial distribution of historical glacier floods in the Swiss Alps and the historical occurrence of heavy damage from mountain torrents, mostly in connection with heavy precipitation (after Zeller (1972)).

have degenerated in the winter, form again. This is also, in general, the time when the water pressure in the glacier sinks and the water stored temporarily is released again from the glaciers (Tangborn and others 1975, Iken and others in press). The release of meltwater sometimes happens in a catastrophic way though. The chronological distribution of events points to the fact that there is no basic (hydraulic) difference between lake outbursts and water-pocket ruptures, apart from the visibility of the stored water, of course!

Outbursts of the largest masses of water have resulted in the best-known glacier floods in the Swiss Alps. These are Lac de Mauvoisin, dammed by Glacier de Giétro, and Mattmarksee, dammed by Allalingletscher, each case involving about 20 x 10^6 m^3. Also, Märjelensee, which is dammed by Aletschgletscher, attained, still in the second half of the last century a volume of about 10 x 10^6 m^3. Gornersee can even today hold about 6 x 10^6 m^3 of water. At the other end of the scale, Kingletscher in Mattertal, Canton Wallis, involving 0.1 x 10^6 m^3, and nearby Rottalgletscher in Saastal, with only 0.01 x 10^6 m^3, are both examples in which small volumes were sufficient to cause local damage from debris flows. The outburst of about 0.12 x 10^6 m^3 of water from a proglacial lake at Vadret da Roseg, on top of a flood brought about by intensive precipitation, resulted in damage of regional dimensions (Töndury 1954). The largest water-pockets contain about 1.5 x 10^6 m^3, but at Vadrec da l'Albigna, about 2.7 x 10^6 m^3 of water were released relatively suddenly in connection with heavy precipitation (Lanser 1959). Figure 3 shows schematic hydrographs of the two most frequent types of outburst. If the ice dam itself is composed of ice debris or if a subglacial channel is blocked for a short time, then a temporary reduction of the discharge below the point of blockage can be followed by a sudden rupture of the ice dam (cf. Ballantyne and McCann 1980). The peak-discharge value is, in such cases, extremely high in comparison to the total discharge volume. Moreover, the peak discharge arrives immediately in the form of a frontal wave, often many metres high.

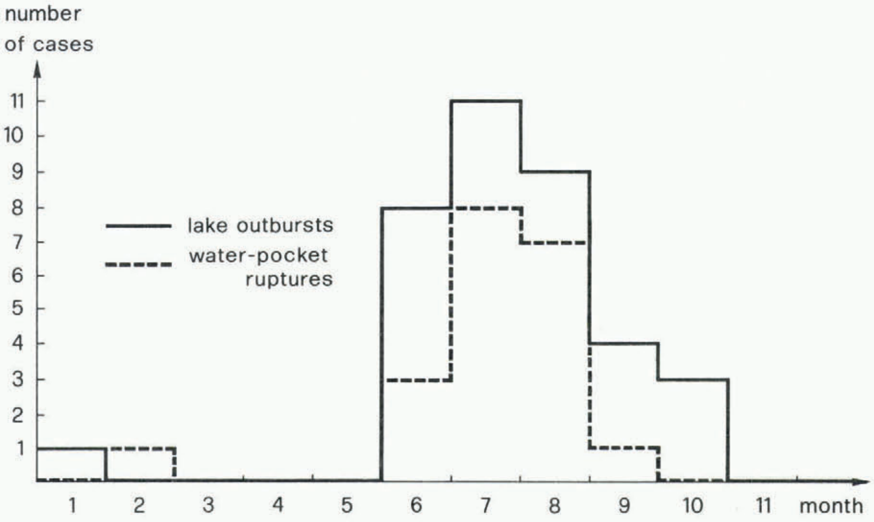

Fig.2. Seasonal distribution of historical glacier floods in the Swiss Alps.

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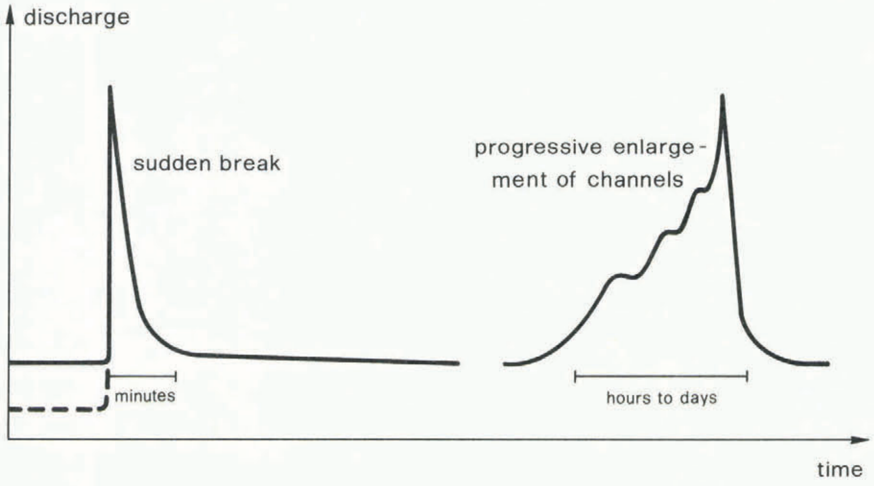

Fig.3. Schematic hydrographs of the two most frequent types of glacier floods in the Swiss Alps. See text for numbers and references.

This type of outburst is by far the most dangerous and, up to now, is almost exclusively responsible for the fatalities caused by glacier floods. Floods caused by progressive enlargement of intra- and subglacial channels, e.g. as is the case with Gorner- and Grubengletscher, are well-documented in glaciological literature (and considerably more popular with theorists, e.g. Nye 1976, Spring and Hutter 1981). Outbursts from proglacial lakes through moraines which contain stagnant ice as, for example, at Steingletscher or at Vadret da Roseg, are poorly documented. In such cases, the hydrographs are probably approximately comparable with those produced by the overtopping of cold ice dams in the Arctic described by Maag (1969).

Observed peak-discharge values are between 8 000 $m^3 s^{-1}$, which occurred after the sudden rupture of the ice-debris dam at Glacier de Giétro (Lanser 1959, Fraser 1966), and 10 $m^3 s^{-1}$, enough to cause damage at the Grubengletscher in 1968 (Röthlisberger 1979). In steep, unconsolidated sediments, peak-discharge values of less than 10 $m^3 s^{-1}$ (e.g. Rottalgletscher and Stammbachgletscher in Canton Wallis) can suffice to trigger debris flows which then cause damage (Haeberli 1981). For the outbursts of the Märjelensee and Gornersee (progressive enlargement of discharge channels in the ice), peak-discharge values of approximately 300 and 200 $m^3 s^{-1}$ respectively were observed (Lütschg 1915, Bezinge 1981). The ratio of debris to water in the total volume of material moved has probably been, in most cases, below 0.35 (e.g. Glacier d'Otemma 1898, Vadret da Roseg 1954, Steingletscher 1956). However, there are also cases known in which this borderline value (part by weight of debris ≈ part by weight of water) has been greatly exceeded (e.g. Kingletscher 1953: 0.8, Grubengletscher 1968: 2.4, Rottalgletscher 1953: 5-10?). It is no coincidence that the highest debris to water ratios have occurred in the dry areas of the Alps and in times of a reduction in glacier length. Neoglacial moraines, which have been recently exposed because of glacier retreat, are particularly prevalent in those dry areas of the Alps where the glacier tongues are high above the tree line and alpine meadow zone. These areas are very rich in unprotected, easily eroded, loose debris. The depth of erosion in such loose material seems to be limited to about 10 to 15 m, since, at greater depths, the bed of the stream becomes paved with large, rough blocks from the exposed side walls. These, thereafter, protect the bed of the stream from further erosion (Haeberli 1981). Erosion channels with a cross-sectional area up to 500 m^2 can occur with modest discharge amounts if the side slopes of channels that are still "unpaved" are inclined at an angle of 20 to 30°. Maximum velocities of the spreading of flood waves in connection with glacier floods in the Swiss Alps are between 20 and 25 km h^{-1} (cf. Lütschg 1915, Walser 1952).

ASSESSING HAZARD POTENTIALS

The examples mentioned above demonstrate that the estimation of risks in connection with glacier floods cannot be made on the basis of one parameter alone

TABLE II. OBSERVED AND ESTIMATED PEAK-DISCHARGE VALUES FOR FLOODS AFTER PROGRESSIVE ENLARGEMENT OF CHANNELS

Year	Glacier	Outburst volume V ($x10^6 m^3$)	Observed peak discharge Q_{max} ($m^3 s^{-1}$)	Estimated peak* discharge $Q_{max(e)}$ ($m^3 s^{-1}$)	$Q_{max}/Q_{max(e)}$
1913	Aletsch (Märjelensee)	4.5	195	205	0.95
1927**	Albigna	2.7	128	146	0.88
1942**	Trient	0.84	26	67	0.39
1944	Gorner	>6	200	250	<0.80
1970	Gruben	0.17	15	23	0.66

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* after Clague and Mathews (1973)
** water pockets

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TABLE III. VOLUME/PEAK-DISCHARGE RELATION FOR KNOWN "SUDDEN BREAK" FLOODS

Year	Glacier	Outburst volume V (m^3)	Peak discharge Q_{max} ($m^3\ s^{-1}$)	V/Q_{max} (s)
1974	Bas d'Arolla	2 000 to 2 500	2.45	816 to 1 020
1952	Ferpècle	255 000	230	1 109
1818	Giétro	20 000 000	8 000	2 500
1951	Unter Grindelwald	135 000	74.6	1 810
1935	Orba (Italy)*	22 500 000	13 000	1 731

(e.g. the surface area of a glacial lake (Post and Mayo 1971)). Rather, the combination of discharge volumes, rupture mechanisms, peak-discharge values, lithology and inclination within the reach of the glacier stream has to be assessed. Outbursts of proglacial lakes with moraine dams containing stagnant ice are, in any case, dangerous and warrant preventive action, since they tend to succeed heavy precipitation events. Thus the discharge may be superimposed onto flooding caused by precipitation. Peak-discharge values for outbursts caused by progressive enlargement of ice channels can be calculated using the entirely empirical Clague-Mathews formula:

$$Q_{max}\ (\text{progressive enlargement}\ (m^3\ s^{-1})) = 75\ (V/10^6)^{0.67}\ ,$$

where V is the outburst volume in cubic metres (Clague and Matthews 1973). Values calculated in this manner are slightly higher than the highest observed peak discharge values (Table II).

The formula is, therefore, admirably suitable for estimates in such cases. However, much higher peak-discharge values are expected in the event of sudden ruptures of ice barriers (Table III). For such events, with the exclusion of the minimal outburst at Glacier Bas d'Arolla, the following formula has to be applied:

$$Q_{max}\ (\text{sudden break}\ (m^3\ s^{-1})) = V/t_w$$

where V is again the outburst volume in cubic metres and t_w is an empirical time constant (about 1 000 to 2 000 s, cf. Table III). In Figure 4, the average slope between the place of rupture and the outermost limit of the recorded area of damage, as a measure of the potential area of damage in the valley, is plotted as a function of the expected value of the peak-discharge. Since the spatial extent of populated areas in the Swiss Alps has not changed significantly over the centuries under consideration, the historical records of events causing damage can be used as a first approximation to appropriate standards. On the other hand, the extent of the damage in comparable cases today and in the future may well be considerably greater because of the expansion of cultivated land in the interim. Based on the relationships represented in Figure 4, the approximate extent of the damaging flood can be estimated. The most extensive damage occurs when there is relatively small debris

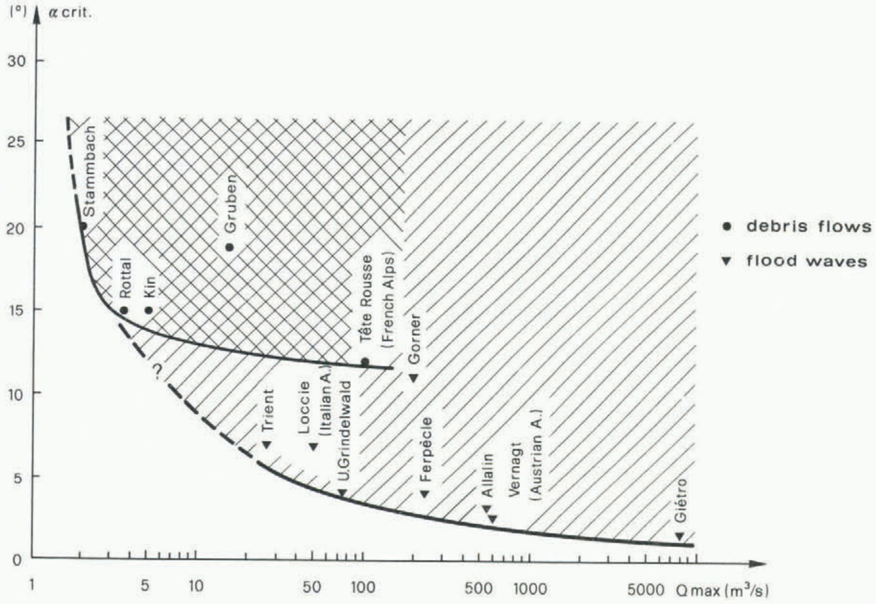

Fig.4. Extent of damage along the glacier stream for sufficiently documented glacier floods in the Swiss Alps. α_{crit} = average slope between the place of rupture (usually the glacier terminus) and the outermost limit of the recorded damage. Events are labelled as "debris flow" when the part by weight of debris exceeds the part by weight of water.

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* Artificial reservoir, data from Fischer and Lippert (1937)

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content. Peak-discharge values below 20 m^3 s^{-1} are dangerous only for slopes over 10 to 12° and when there is, in addition, readily eroded loose material. The relationship given in Figure 4 also takes into account a few (known to the author) well-documented, non-Swiss glacier floods in the Alps, especially the catastrophe on Glacier de la Tête Rousse 1892, French Alps (sudden waterpocket rupture, many people killed in St Gervais (Mougin and Bernard 1922)), and at Vernagtferner, Austrian Alps (repeated sudden dumping of the Rofen lake, dammed-up during and after the surges of Vernagtferner, damages right into the Inntal: Lanser 1959, Hoinkes 1969). These are, however, extreme events historically. Many glacier floods take place and terminate well within the indicated extremes. These extremes have to be taken as standards, however, until the reasons are known why it is that, in some cases, the limits are not being reached.

CONCLUSIONS

Damages in connection with glacier floods are still to be expected in the Swiss Alps in the foreseeable future, but because of the retreat of glaciers and the construction of reservoirs for power production, it will mainly be a question of outbursts of relatively small water masses in easily eroded, loose sediments. For the estimation of such glacier hazards, which are usually local, one has to call on experience from historical events. Peak-discharge values can be calculated approximately, using the Clague-Matthews formula, as long as the sudden break of an ice dam is not suspected; this may occur after the surge of a glacier, an ice avalanche or a temporary blockage of a subglacial discharge channel. If this is the case, then the discharge per second can reach 1/1000 of the outburst volume and a flood wave of many metres in height may ensue. When the slope is steep, even small outburst volumes and modest peak-discharge values may result in the formation of dangerous debris flows. In suitable material (20 to 30° steep moraine slopes, scree slopes or rock-glacier fronts), erosional channels with a cross-sectional area of up to 500 m^2 can form. The largest, unpredictable peak-discharge values from glacierized areas are observed in connection with water-pocket ruptures, as a consequence of progressive enlargement of intra- and subglacial channels in connection with heavy precipitation, and also from sudden water-pocket ruptures after temporary blockage of discharge channels. Such values are of the order of 100 to 150 m^3 s^{-1}. For centuries, many mountain villages have been situated where they may be affected by such events which, on the one hand, are very rare, and on the other, may well have serious consequences in the future.

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