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GLACIER HAZARDS AT BELVEDERE GLACIER AND THE MONTE ROSA EAST FACE, ITALIAN ALPS: PROCESSES AND MITIGATION

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ABSTRACT

In summer 2001, the Belvedere glacier, Macugnaga, Italian Alps, started a surge-type movement with ice velocities increased by one order of magnitude. A lake of 3 million m³ in volume formed on the glacier during spring 2002. Rapid emergency actions were initiated by the Italian Civil Defense Department. This included evacuation of certain parts of the village of Macugnaga, automatic alarm systems, installation of pumps, and detailed scientific investigations. Significantly reduced melt water input in July 2002, together with naturally developing sub-glacial drainage, helped to stabilise and then lower the lake level. In spring 2003, however, the lake developed again. In mid-June 2003, the lake burst out within a few days, without causing any damage. Besides, the advancing Belvedere glacier causes extensive rock- and ice-fall activity, overruns tourist installations and destabilises its moraines. In the Monte Rosa east face, enhanced rock-fall activity is observed. A drastic decrease in glaciation of the flank uncovers large rock areas and changes the thermal regime of the wall.

Key words: Belvedere, glacier hazards, hazard management, surge, glacier lake outburst

INTRODUCTION

Glacier- and permafrost-related hazards increasingly threaten human lives, settlements, and infrastructure in high-mountain regions. Present atmospheric warming particularly affects terrestrial systems where surface and sub-surface ice is involved. Changes in glacier and permafrost equilibrium are shifting beyond historical knowledge. Human settlements and activities are extending towards danger zones in the cryospheric systems. A number of recent glacier hazards and disasters underscore these trends (Kääh et al., 2003b).

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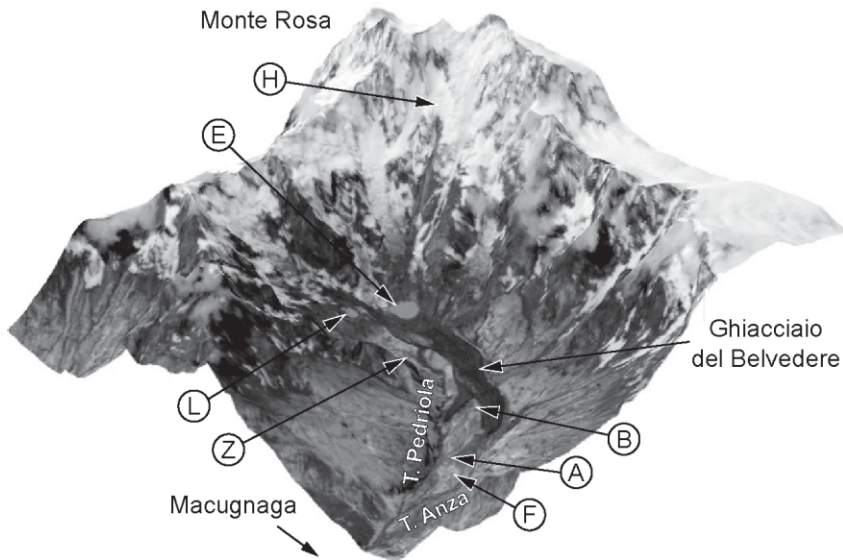


Fig. 1: Oblique perspective view on Ghiacciaio del Belvedere and Monte Rosa from the Northeast. The synthetic view is computed from ASTER data of 19 July 2002, and a digital terrain model from photogrammetry and ASTER stereo data. Section size is approximately 8 x 8 km. For the letters see the text.

One of the most-followed recent cases is the development at the Monte Rosa east face and the Belvedere glacier (Ghiacciaio del Belvedere, Macugnaga, Italian Alps). The type and magnitude of processes and hazards involved make this case of special scientific interest, and confront the responsible authorities with complex problems without precedent in the European Alps.

BACKGROUND

Ghiacciaio del Belvedere is a humid-temperate glacier with a flat, heavily debris-covered tongue and fed by steep glaciers, ice and snow avalanches as well as rock falls from the large east face of Monte Rosa (Fig. 1). It has been investigated for many decades and is known as a classic example of a glacier with an elevated sediment bed (cf. Mazza, 1998).

At least seven outburst floods are known to have originated from the glacier in the past, threatening the village of Macugnaga, damaging infrastructure, and affecting the original moraine geometry (Haerberli et al., 2002):

- August 1868: water pocket outburst and moraine collapse at the left tongue
- August 1896: moraine breaching after heavy rainfall
- 1904: water pocket outburst and cutting through the right lateral moraine
- September 1922: water outburst from the glacier after a rainfall period
- August 1970, August 1978, July 1979: outburst floods from the Lago delle Locce.

In July 1979, Lago delle Locce (L in Fig. 1) broke out through/underneath its ice dam towards Ghiacciaio Nord delle Locce. The flood wave travelled through the natural channel between the

Ghiacciaio del Belvedere and its right lateral moraine. At a slight counter-slope near Rifugio Zamboni (Z in Fig. 1), the flood cut through the moraine progressively eroding a large breach. The subsequent debris flow seriously damaged the Belvedere chair-lift and flooded the valley bottom for a length of 1 km and a mean width of 150 m, almost reaching the hamlet of Pecetto near Macugnaga. Following the 1979 flood, prevention work such as artificial lowering of the lake level at Lago delle Locce and dam construction in the main torrent below the glacier became necessary (Haerberli and Epifani, 1986; Mazza, 1998).

From the mid-1980s until 2001 no unusual situation at Ghiacciaio del Belvedere was encountered. In summer 2001, however, heavy crevassing of the glacier surface, a marked increase in thickness, dirty ponds between the glacier and its lateral moraines, and enhanced ice- and rock-fall activity from the glacier margins were observed. The processes were interpreted as indicators for a surge-type glacier movement and the local authorities instructed (Haerberli et al., 2002). As a consequence monitoring of the area was intensified.

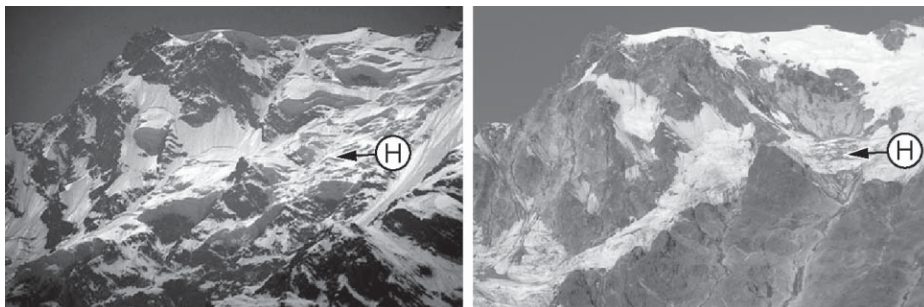


Fig. 2: Upper part of the Monte Rosa east face in the mid-1980s (left) and on 6 August 2003 (right). Some steep glaciers have totally disappeared; some have significantly lost mass. Zones of increased rock-fall activity are to the right of the right image, above and below a steep hanging glacier (H). To the very right of both images is the well-known Marinelli ice couloir, which has become largely ice-free by summer 2003.

SLOPE INSTABILITIES IN THE MONTE ROSA EAST FACE

The Monte Rosa east face is one of the highest flanks in the Alps (c. 2200-4500 m asl.). Its glaciation by steep hanging glaciers underwent distinct changes during the recent years (Fig. 2). Some glaciers and uncrevassed ice covers have totally disappeared leaving large parts of the underlying rock unprotected against mechanical and thermal erosion (cf. Davies et al., 2001; Noetzli et al., 2003). Roughly one half to two thirds of the east face are estimated to be under permafrost conditions. The three-dimensional permafrost distribution and its spatio-temporal evolution are closely linked to the ice and snow cover of the face (and vice-versa). Thus, the well visible decrease in glacierization is most likely accompanied by a less visible but, nevertheless, also marked change in the thermal regime of the Monte Rosa east face.

Recently, especially heavy ice- and rock-fall activity originates from two zones south of the Imseng ridge (Fig. 2). The two rock-fall source areas are situated below and above a hanging glacier (H in Figs. 1 and 2), which itself undergoes rapid geometric changes and frequently releases ice-falls. In 2001, this hanging glacier still had an approximately 30 m high vertical front as typical for hanging glaciers (cf. photo in Haerberli et al., 2002). Since summer 2002, this front

has largely diminished, and the glacier shows heavy crevassing and mass loss (Fig. 2). Already in 2000, a steep glacier covering the lower of the presently active rock-fall source areas disappeared (Fig. 2). Mass wasting from the lower rock-fall zone is not only by single rock-fall events but frequently also by debris flows, which are presumably triggered by melt water. The continuation of rock-fall activity during the winter-months points to a substantial change in glacier and rock conditions rather than to seasonal melt effects alone.

The major concern related to these instabilities in the Monte Rosa east face is whether they are part of a destabilisation of a large rock mass, which could trigger events comparable to the rock avalanche at Brenva, Mont Blanc, in 1997 (Barla et al., 2000; Deline, 2001; Giani et al., 2001), or the 2002 Kolka/Karmadon rock/ice avalanche, Caucasus (Haerberli et al., 2003; Käab et al., 2003c). Presently, large rock and/or ice avalanches cannot be excluded and are potentially able to trigger, for instance, large snow avalanches, a lake outburst flood, or major ice break-offs. Due to the high vertical distance of fall, the potential horizontal travel distance of such events could reach several kilometres.

A SURGE-TYPE MOVEMENT OF GHIACCIAIO DEL BELVEDERE

Since spring 2001 (possibly already starting in autumn 1999; Mazza, 2003), Ghiacciaio del Belvedere has experienced drastic changes in flow regime and related features. Starting at the foot of the Monte Rosa east face and continuing downwards the glacier, exceptional crevassing indicated high stresses and strain rates in the ice. As a consequence, the surface characteristics of the glacier changed from almost complete debris-cover with smooth topography towards a roughly crevassed topography with debris-cover only in parts left (Figs. 3 and 6). In the mid-1980s and during 1995-1999, average surface speeds on the lower part of Ghiacciaio del Belvedere were found in the order of up to 40-45 m a⁻¹, or 35 m a⁻¹, respectively (VAW, 1985; Käab et al., 2003a; cf. Mazza, 2003). During 1999-2001 average speeds of up to 110 m a⁻¹ and during autumn 2001 of up to 200 m a⁻¹ were observed photogrammetrically. Terrestrial surveying and photogrammetry in summer 2002 yielded speeds of up to 80 m a⁻¹. In spring 2003, a distinct, few metres wide shear band at the margins of the snow-covered glacier indicated the continuation of the exceptional speeds (S in Fig. 4). The surface deformation on the glacier between the marginal zones seems to have been low enough not to rip up the snow cover.

At most parts of the glacier its speed-up was accompanied by an increase in ice thickness of 20 m and more. The corresponding mass shift travelled down the glacier reaching its maximum at Belvedere (B in Fig. 1), for instance, around summer 2002 (cf. Mazza, 2003). Presently (August 2003), ice thickness diminishes again on most parts of Ghiacciaio del Belvedere. First photogrammetric analyses suggest that the enhanced movement was first of all restricted to the flat lower part of the glacier. The large depression at the foot of the east face, which was temporary filled by a supraglacial lake (E in Fig. 1; cf. section below), might partially originate from strong extending flow and, thus, mark the upper limit of the primary surge-type movement. The heavy crevassing observed for the glacier parts above the depression zone could, thus, be the consequence of a drastically changed stress regime due to sudden lack of support at the slope foot, rather than active part of the speed-up event.

Photogrammetric studies show that already during 1995-1999 a total loss in ice thickness of about 20 m occurred at the location of the depression. The ice thickness of the other glacier parts remained comparably stable during the same time period.

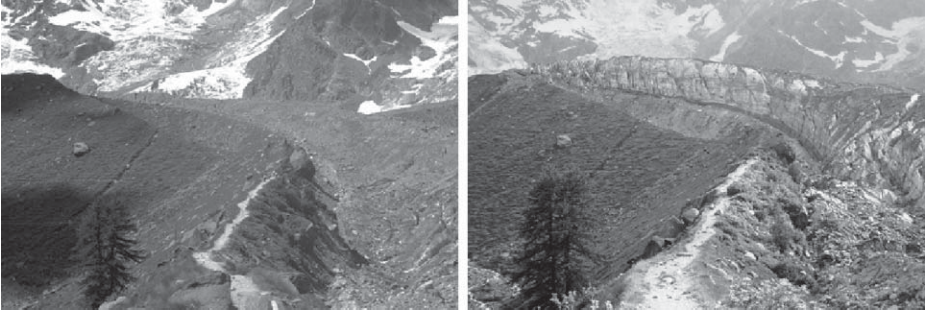


Fig. 3: Orographic right lateral moraine and ice margin of Ghiacciaio del Belvedere as seen to the upward direction of the glacier (left: summer 1996; right: end of June 2002). The ice wall to the middle of the right image is approximately 20 m high.

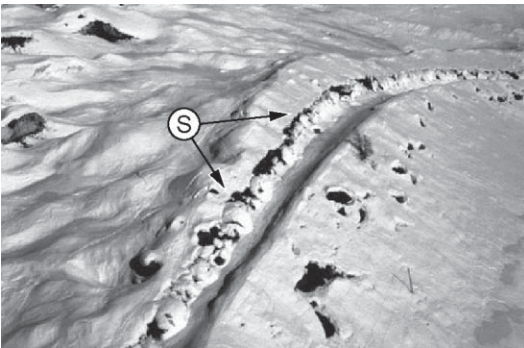


Fig. 4: Orographic right margin and lateral moraine of Ghiacciaio del Belvedere as seen on 10 March 2003. See telephone mast (to the lower right) and a pair of trees (to the middle right) for scale. An active shear band (S) at the glacier margin indicates high glacier speed.

Beyond these findings, the mechanism of the surge-type movement of Ghiacciaio del Belvedere since 2001 remain still unclear (cf. Mazza, 2003). Enhanced basal water pressure seems to have been involved as suggested by dirty ice-marginal ponds in 2001 (Haeberli et al., 2002) and the evolution of a huge supra-glacial lake in 2002 and 2003 (see section below on the supra-glacial lake). An ice-marginal band of strong shearing combined with an undisturbed snow cover on the glacier surface itself, as observed in winter 2002/2003 (S in Fig. 4), indicate that the glacier moved as a block by sliding, sediment deformation or internal shearing rather than by enhanced deformation throughout the entire ice column (cf. Raymond, 1987; Harrison and Post, 2003). Hazards related to the enhanced glacier speed and mass transport include increased rock- and ice-fall activity at its margins, overrunning of infrastructure and installations, and destabilisation of moraines (cf. section below on glacier advance). The end of the surge could be accompanied by a sudden outburst of pressurised dammed water. Shearing-off of even large glacier parts cannot be excluded as shown by the 2002 Kolka/Karmadon avalanche, a situation which displays some similarities to the present case (Kääb et al., 2003c).

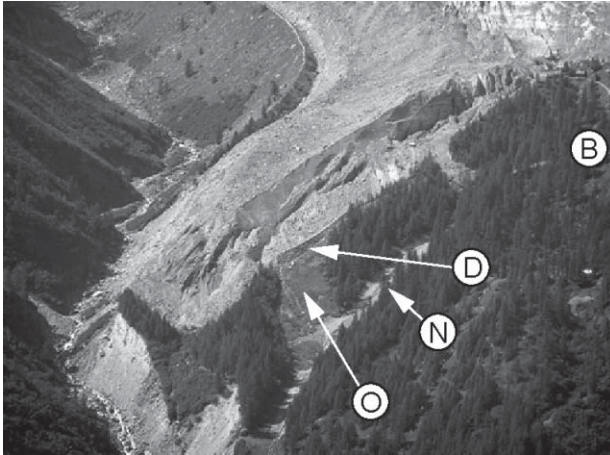


Fig. 5: The orographic right tongue of Ghiacciaio del Belvedere, between Torrente Pedriola (left) and Belvedere (B; 6 August 2003). The glacier overruns its historic moraines. A new ski run (N) replacing the old ski run (O) and an ice- and rock-fall retention dam (D) were constructed in autumn 2002.

GLACIER ADVANCE AND ITS CONSEQUENCES

As an expression of its elevated bed the surface of Ghiacciaio del Belvedere more-or-less had the same elevation as its historic lateral moraines already before 2001. As a consequence of the recent surge-type movement, however, the glacier surface vertically exceeded the lateral moraines by up to 20 m. At some locations the glacier overran its moraines producing frequent ice- and rock-falls over the outer moraine slope. The access trail to the Rifugio Zamboni CAI (Z in Fig. 1) and further to the Lago delle Locce (L in Fig. 1) partially had to be closed in 2002 and a detour constructed. In some places well visible, the enhanced lateral pressure from the surging and advancing glacier led to weakening or even first cutting through the moraines. As potential moraine breaks, such situations are of major concern in view of enhanced runoff or glacier floods running between the glacier and the moraine (cf. the 1979 flood in the "background section" and the section below about the glacier lake). Even after a complete stop of the accelerated movement, large ice blocks could continue to deform or slide individually and, thus, further damage the lateral moraines. The corresponding weak points in the moraines remain for extended time periods.

At the location 'Belvedere' (B in Fig. 1) at the divergence between the two tongues of Ghiacciaio del Belvedere, the glacier advance led to a special situation (Fig. 5). Already in summer 2001, but most noticeable since winter 2001/2002, the glacier started to overrun its lateral moraines along the entire left side of the right tongue. The material cable-lift from Belvedere to Rifugio Zamboni across the glacier had to be closed already in autumn 2001. The trail crossing the glacier towards the Rifugio was closed in 2002 and had to be repeatedly rebuilt after its re-opening. Extensive rock- and ice-falls reached the old ski run (O in Fig. 5) and increasingly buried it as well as the forest and the hiking trail along the outer moraine slope (Fig. 5). In autumn 2002, a new ski run (N in Fig. 5) was constructed to avoid the direct danger zone. A blocky retention dam of approximately 100 m length (D in Fig. 5) was built for holding back rock- and ice-falls towards the ski run and towards the middle station of the chair lift at Alpe Burki (A in Fig. 1). A further

point of major concern is the very terminus of the advancing right tongue. It descends into the steep flanks of the Torrente Pedriola. Heavy erosion in the river-bed (e.g. due to a glacier flood) or destabilisation within the ice mass itself could lead to ice break-offs and subsequent temporary blockage of the river. Furthermore, rock- and ice-fall events from the right tongue could have considerable run-out distances, especially with reduced friction due to snow cover in wintertime.

EVOLUTION AND OUTBURST OF A SUPRA-GLACIAL LAKE

Possibly as a consequence of enhanced englacial water pressure (indicated by ice-marginal ponds; cf. picture in Haerberli et al., 2002) or other processes related to the surge-type movement, a supra-glacial lake of about 3500 m² developed in September 2001 on the Ghiacciaio del Belvedere at the foot of the Monte Rosa east face (Haerberli et al., 2002; Mortara and Mercalli, 2002). In October 2001 the lake reached an area of about 20,000 m². During winter 2001/2002 the corresponding depression enlarged presumably due to strongly extending ice flow (cf. section above on the surge-type movement). By the end of May 2002, the lake had an area of roughly 20,000-40,000 m² as reconstructed from ASTER satellite imagery (Kääb et al., 2003c). It was with great surprise, that the first control visit in mid-June 2002 encountered an exceptionally large lake of nearly 150,000 m² with a volume of 3 million m³ (Fig. 6). The lake level was rising by up to 1 m per day and had only a few metres of freeboard left. At the right margin of the lake the hydraulic head within the ice dam must have been far over 10%.

The Italian civil defense authorities and the scientists involved initiated emergency actions (cf. section below on hazard management). Due to the high hazard potential involved the exact volume of the lake was measured by bathymetric soundings at the beginning of July 2002 in order to obtain parameters necessary for planning the capacity and location of pumping installations, and assess their potential efficiency (Tamburini et al., 2003). The maximum lake level was reached on 26/27 June 2002; the maximum lake depth amounted to about 60 m. Possible processes of lake formation and growth are discussed by Chikita et al. (1999), Benn et al. (2000), Reynolds (2000), and Kääb and Haerberli (2001).

A cold spell in early July 2002 (Regione Piemonte, 2002) significantly reduced melt water input, and together with pumping and naturally occurring sub-glacial drainage, helped to stabilise and then lower the lake level slowly. By the end of October 2002, the lake area had decreased to a size comparable to that of autumn 2001 (cf. photo in Tamburini et al., 2003). For understanding the sub-glacial drainage characteristics and in view of potential future reformation of the so-called Lago Effimero (short-lived lake; E in Fig. 1), tracer experiments were performed in mid-October 2002 (Tamburini et al., 2003). Sodium-fluorescein was poured through a hose at a water depth of about 10 m near the northern margin of the lake. The tracer was first discovered after 24 hours at the moraine sources between the two glacier tongues (Fontanone; F in Fig. 1) and the orographic left glacier outlet (Torrente Anza) with peak concentrations after two and four days, respectively. No tracer was found at the sources in the moraine breach near Rifugio Zamboni and the outlet of the right glacier tongue (Torrente Pedriola).

From ground-based seismic and radar soundings in the mid 1980s (VAW, 1985), helicopter-based radar soundings in 2002 (Tamburini et al., 2003), and again ground-based radar soundings in spring 2003, Ghiacciaio del Belvedere is known to be up to 200 m thick and possibly underlain by bedrock along the section between the foot of the Monte Rosa east face and Rifugio Zamboni. Further down, the glacier was found to be up to 150 m thick and resting on a sediment bed of several tens of metres thickness. This counter-slope in the sediment bed seems to form an overdeepening of Ghiacciaio del Belvedere near Rifugio Zamboni. Together, (i) the probable

existence of a sediment riegel, (ii) the long travel time of the tracer compared to the travel times found for sub- and en-glacial channels (Schuler, 2002), and (iii) the fact that the major tracer release was at a moraine source well apart from the glacier streams may point to a lake drainage through the sub-glacial sediments.

In spring 2003, the large depression at the location of the Lago Effimero rapidly refilled with melt water reaching a volume similar to the one found in end of June 2002. In fact, the 2003 Lago Effimero was similar to the one of 2002 with respect to surface shape as well (Fig. 6). Its water level was about 10 m a.s.l. deeper compared to 2002, presumably as an effect of continued ice thickness loss due to further glacier extension and melt.

Between 18 and 20 June 2003 Lago Effimero burst out. On 18 June 2003, a day of fine weather but without especially enhanced melting conditions, increasing discharge of very dirty water from the left glacier tongue (Torrente Anza) was observed. At the same time the automatic monitoring systems for the water level of the lake and for the flow height of the Torrente Anza at Pecetto showed unusually de- and increasing values, respectively.

Torrente Anza experienced above-average flow-heights from 18 to 20 June, with maximum values on 19 June. Corresponding maximum discharge was estimated to have been in the order of $15\text{-}20\text{ m}^3\text{ s}^{-1}$. The maximum lake level before the outburst was reached on 16 June. Within a few days the lake level dropped by about 20 m and about 2.3 million m^3 were released.

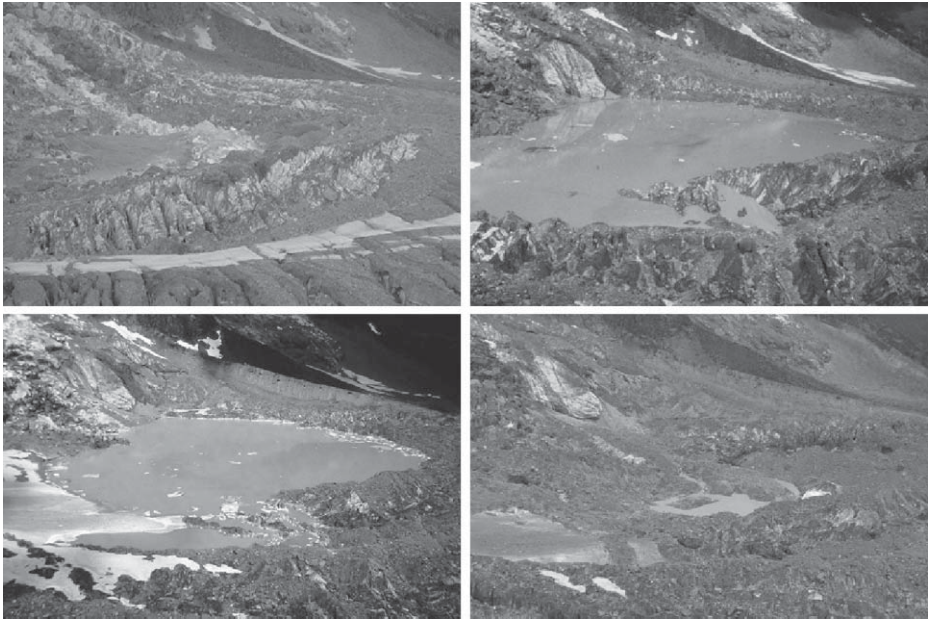


Fig. 6: Location of Lago Effimero as seen from the moraine bastion near Lago delle Locce: 17 July 2001 (upper left), 26 June 2002 (upper right), 18 June 2003 (lower left), 5 August 2003 (lower right).



Fig. 7: At a short section the sub-glacial lake outburst flood partially reached the surface between the glacier and the orographic left lateral moraine (18 June 2003). Photo taken from helicopter in upvalley direction. The arrow indicates the flow direction.

The outburst peak was reached on 19 June with a 24h-loss in lake level of about -8 m, loss in volume of -1.0 million m³, and equivalent discharge of 12 m³ s⁻¹ (24h-average). The outburst path occurred en- and/or subglacially towards the orographic left glacier gate (Torrente Anza). During the outburst, along a short section of roughly 100 m length, a dirty stream between the ice margin and the left lateral moraine became visible (Fig. 7). Strong rumbling from boulders displaced by heavy runoff could be heard at that section also from underneath the glacier indicating that only parts of the flood reached the surface.

The lake outburst of mid-June 2003 clearly showed that a supra-glacial lake on Ghiacciaio del Belvedere has a potential for a catastrophic flood. From a volume of 3 million m³ a maximum outburst discharge in the order of up to 100-200 m³ s⁻¹ can be expected in case of a hydraulic ice dam break (i.e. progressive enlargement of en-glacial flow channels; Clague and Mathews, 1973; Walder and Costa, 1996). Mechanical breaking of an ice dam (very unlikely under the present topographic conditions) or temporary runoff blockage through ice collapses at the glacier margins or under the glacier could, however, result in even higher discharge. Especially the orographic right glacier stream (Torrente Pedriola) carries an amount of erodable debris, which is apparently large enough for a debris flow to be triggered by a glacier flood.

FUTURE DEVELOPMENTS

The near to medium-term future of the Monte Rosa east face and the Ghiacciaio del Belvedere will most likely be characterised by drastic and rapid changes in glacier and permafrost conditions. The exceptionally hot summer 2003 has accelerated trends, which, however, have to be expected anyway from the past and ongoing atmospheric warming and the delayed reaction of terrestrial surface- and subsurface ice occurrences.

The drastic loss in ice cover on the Monte Rosa east face will cause mechanical and thermal adjustments of ice and rock, on and in the wall. High rock- and ice-fall activity will, therefore, most likely continue. Large events cannot be excluded.

The substantially decreasing ice supply from the Monte Rosa east face to the lower part of Ghiacciaio del Belvedere (cf. Mazza, 2003) will largely decouple the lower glacier part from its accumulation areas. Already now (August 2003), about 50 % of the former glacier width at the foot of the east face have become ice-free. The remaining ice-flux is clearly not sufficient to balance the mass loss through ablation on the lower part of Ghiacciaio del Belvedere. Related glacier shrinkage will, however, be damped by the debris-cover. As a consequence of decreasing ice-flux into the depression of Lago Effimero and continued extending flow, this depression might substantially increase in volume. While such development might favour a new formation of Lago Effimero in 2004, the evolution of the equally important characteristics of the damming body are unclear (changes of en- and sub-glacial water pressure? Changes in permeability of the sediment bed?). Besides the hazards from a supra-glacial lake, a growing (and empty) topographic depression at the foot of the Monte Rosa east face might, on the other hand, act as a valuable retention basin for ice and rock avalanches.

Even after the surge-type movement of Ghiacciaio del Belvedere has come to an end, some individual ice masses will independently continue to deform and slide. An area especially affected by such process might be the quite steep right tongue. Related overrunning of moraines, and rock- and ice-fall activity will, thus, continue. In addition to mechanical destabilisation of moraines, weakening by infiltration of meltwater from melt of the accumulated ice masses might take place.

HAZARD MANAGEMENT

The development of a large topographic depression on the glacier surface and the rapid evolution of a supra-glacial lake are rare on temperate glaciers, and have not been previously observed in the Alps in this dimension. In view of the large, unusual and fast developing threat, which the 2002 Lago Effimero posed to the down-valley areas, the Italian National Department for Civil Defense (Dipartimento di Protezione Civile) took over by decree the responsibility at beginning of July 2002. In such a case, the command over the involved parts of the armed forces, fire departments, police departments, regional and local authorities etc. is transferred by law to the operation leader within the Protezione Civile (Legge 225, 1992). As a consequence, the actions necessary in July 2002 could be performed with high efficiency and with a considerable effort in personnel and material. Emergency actions included continuous monitoring of the level of the Lago Effimero, survey of the moraine stability carried out twice a day by alpine guides and volunteers of the Macugnaga Alpine Rescue, video cameras at the lake and the glacier rivers, an automatic alarm system, evacuation of certain parts of the village of Macugnaga, and the installation of a pump system at the lake (Regione Piemonte, 2002).

After these high-level emergency actions and substantial hazard reduction due to the decrease in lake volume (cf. section above on the glacier lake), the responsibility was transferred to the technical and civil defense authorities of the Regione Piemonte in mid-July 2002 (Regione Piemonte, 2002). Over winter 2002/2003 mitigation plans were elaborated for the case of a new formation of Lago Effimero in 2003. Planned measures included pumps mounted on a cable crossing the glacier and artificial outlet channels through ice and moraines. Due to uncertainties in the lake development, and in technical and financial issues it was decided to prepare but not perform emergency actions and to put into service again the monitoring and alarm system.

During the lake outburst in mid-June 2003, warning and alarm thresholds for river discharge and changes in lake-level were set up, and additional monitoring personnel placed at critical points. The local authorities prepared evacuations. The Belvedere chair lift and endangered trails were, like already in 2002, temporarily closed.

Present scientific activities are directed towards an integrated hazard assessment not only covering the Lago Effimero but also the geological and glaciological conditions of the Monte Rosa east face, the surge-type movement and related glacier advance, and slope stability issues concerning Ghiacciaio del Belvedere and its moraines. A major focus has to be put onto possible chain reactions combining several of the above hazards. An extensive monitoring program is crucial in order to early recognise critical developments.

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