Name of research institute or organization:

Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie (VAW), ETH Zürich

Title of project:

On the outburst of glacier-dammed lakes: A study at Gornergletscher, Valais[1]

Project leader and team:

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Project description:

The release of water from glaciers in catastrophic floods poses an important threat to human activity. Such events are called *jökulhlaups*, an expression from Iceland, where spectacular outburst events originate in large water bodies impounded within ice caps. These lakes form when a geothermal area melts ice from the base. In the Alps or in glacierized mountain areas in general, glacier-dammed lakes develop in a depression resulting from a combination of topographical conditions and glacier extent. They also form in depressions on the irregular surface of debris-covered glaciers. The most famous historical cases in the Swiss Alps, where such glacier-dammed lakes suddenly drained with disastrous consequences, are *Glacier du Giétro*, *Allalingletscher*, *Grubengletscher* and *Aletschgletscher/Märjelensee*. These outbursts represent a severe threat in mountain ranges and have caused major damage and loss of life in the past.

Lakes impounded behind an ice barrier drain in a variety of ways. Among the most well known are lake outbursts associated with a catastrophic drainage due to rapid thermal enlargement of subsurface channels. But sometimes, for unknown reasons, other mechanisms occur, even at the same location, owing to the complex nature of these events. The initiation of an outburst may be of particular complexity. The ultimate challenge of this phenomenon is clearly to be able to predict the timing and magnitude of lake outbursts. In spite of recent improvements in the physical understanding of flood mechanics, such forecasts are not yet possible. This was the main motivation for the launching of a comprehensive project by the VAW, Glaciology Section, three years ago on *Gornergletscher* above *Zermatt*.

Observations

Gornergletscher is the second largest glacier in the Alps (Fig. 1). It consists of several tributaries and covers an area of nearly 60 km².

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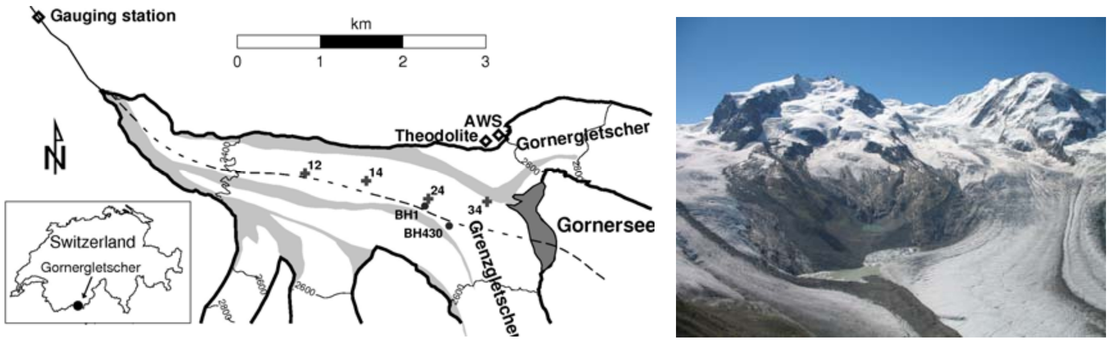

Fig. 1: Map of *Gornergletscher* (left). Dots mark two boreholes and crosses indicate the position of four stakes for ice motion measurements. The central flowline used for the profiles in Figure 2 is depicted by a dashed line. Photograph (right) taken in July 2006 showing *Gornergletscher* and its two tributaries *Grenz-* and *Gornergletscher* (right and left) and *Gornersee* (at the confluence).

At the confluence of *Gorner-* and *Grenzgletscher*, *Gornersee* (an ice-marginal lake) has formed every spring and drained every summer for many years. In the last century *Gornergletscher* experienced a significant ice loss, especially in the lake area (150 m thinning since 1931, Fig. 2) leading to a continuously changing bathymetry. The greatest ice thickness of *Gornergletscher* is 450 m and the main glacial valley is slightly over-deepened.

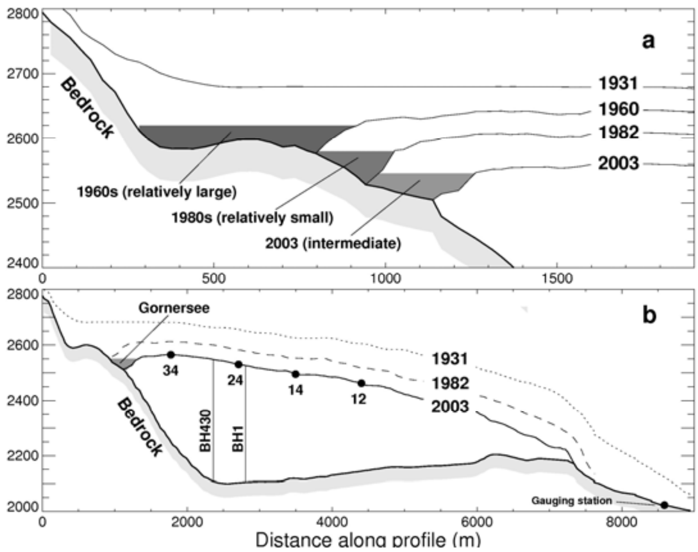

Fig. 2: (a) Schematic profile of the Gornersee evolution during the past decades. **(b)** Longitudinal profile of the Gornergletscher tongue. Bed topography was obtained from radio-echo soundings. Two boreholes and four stake locations are indicated.

A gauging station operated by the *Grande Dixence* hydropower company is situated 1 km downstream of the glacier terminus, recording hourly discharge since 1970 and additional observations of the lake drainage in the 1950s and 1960s, providing the unique possibility to carry out an assessment of glacier floods for more than half a century. Each year 1 to 5 Mill. m³ of meltwater are impounded by the lake. In most of the cases, the lake filled to the maximum level beyond which it would give rise to a supraglacial outflow and start to drain subglacially shortly after. Since 2004, we have performed a variety of field experiments to explore the lake outburst phenomena, including: (1) velocity measurements with high temporal and spatial resolution, (2) passive seismic activity recording, (3) dye-tracing, and (4) water pressure and tilt measurements in boreholes drilled in the glacier. In 2004, we observed a supraglacial outflow for a few days before water left the basin subglacially. In 2005 the lake drainage started subglacially with a surface water level 15 m lower than 2004, well before supraglacial outflow could occur. In 2006, the lake filled completely and drained within roughly three weeks by melting a 300 m long and 50 m deep gorge in the ice dam. The water then flowed through a *moulin* and escaped from the glacier subglacially. According to these observations, three different drainage processes occurred in three consecutive years. This indicates the difficulties encountered in attempting to forecast such events.

Lake outbursts 1950-2006

The discharge from lake outbursts is superimposed on melt-precipitation induced by runoff variations. Because we have discharge records from the *Grande Dixence* gauging station only, it was necessary to conduct a hydrograph separation to identify the magnitude and timing of previous lake outbursts. We applied a distributed temperature-index melt model coupled with a linear-reservoir runoff model to compute hourly discharge from the *Gornergletscher* catchment. By subtracting the simulated melt-precipitation induced discharge from the discharge measured at the gauging station, we extracted the outburst component of the hydrograph (Fig. 3).

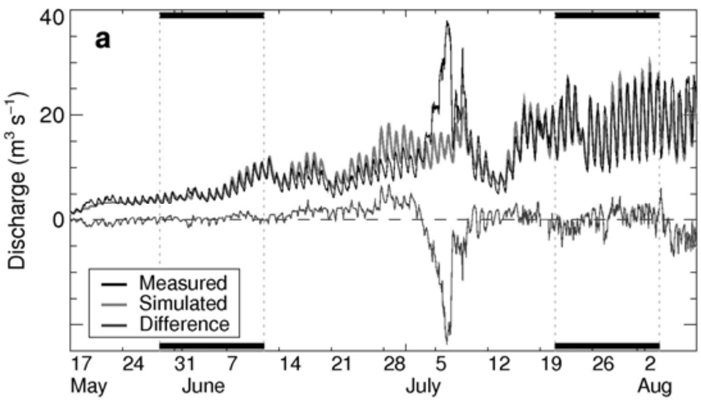

Fig. 3: Measured and simulated hourly discharges of *Gornergletscher* during summer 2004. The lake drainage event is clearly identified.

Significant drainage events were identified in each year except for 1984, 1991, 1995 and 2006. Figure 4a presents the evolution of the lake outburst timing revealing an obvious trend. Between 1950 and 2005, a shift of about two months was observed, moving the expected date of the event from late August to late June. In contrast, the temporal evolution of drainage volume does not show a uniform trend (Fig. 4b).

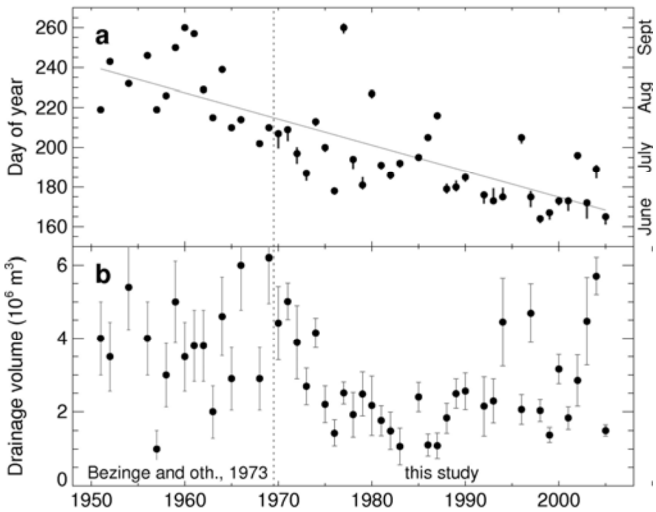

Fig. 4: (a) Evolution of lake outburst timing. (•) correspond to the dates of peak discharge. Vertical bars show the duration of the drainage events. **(b)** Time series of drainage volumes with corresponding error bars.

It is not clear to what extent the volume fluctuations are caused by the changing lake basin geometry or the different filling levels of the lake. Clague and Mathews (1973) first suggested that the peak discharge Q_{max} and the water volume V drained by an ice-dammed lake during the flood appears to follow a power low relation of the form $Q_{max}=K\,V^b$, where K and b are constants determined from field data. This relation can be used to estimate the flood magnitude but is not suitable for accurate predictions. Subsequent extended studies with more data revealed a greater scatter, but the value of the exponent (b=2/3) seemed robust for subglacial lake outbursts. Recently, Ng and Björnsson (2003) demonstrated the physical origin of this formula and discussed the numerical value of the exponent. By analyzing the data obtained from *Gornersee* between 1950 and 2005, we found the same relation as Clague and Mathews (1973) but with a much smaller value of K=10 instead of 75 (Fig. 5).

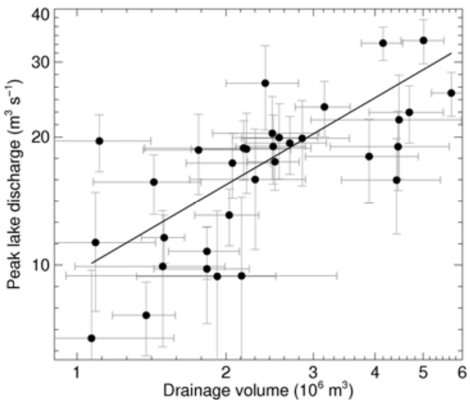

Fig. 5: Log-log-plot of drainage volumes and peak lake discharges (number of samples n=33 and correlation coefficient r^2=0.61).

Considering the range of drainage volumes of *Gornersee*, which is much smaller than in the previous studies, the two variables show a strong correlation (Fig. 5). Nevertheless, the scatter in Figure 5 indicates that the previous relation is not yet practicable for a reliable forecast. This unique 50-year time series of annual lake outbursts demonstrates the complexity and diversity of the lake outburst process.

Mechanisms of lake outburst

Present theories postulate that the drainage of glacier-dammed lakes is controlled by two different processes:

(1) Progressive enlargement of intra- or subglacial water channels, and

(2) Flotation of the ice dam.

The intra- or suglacial channels have been called Röthlisberger- or R-channels since Hans Röthlisberger, VAW, first published a pioneering article on this subject in 1972. This channel enlargement process induces a gradual climb of the hydrograph. On the other hand, flotation of the ice dam produces a sharp and sudden runoff peak which happens when the subglacial water pressure exceeds the ice overburden pressure.

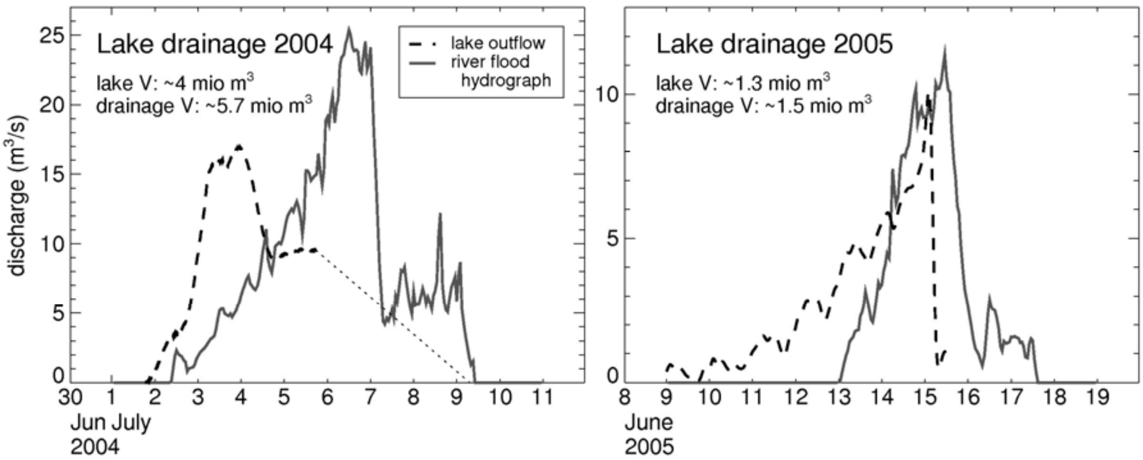

Fig. 6: Outburst from *Gornersee* and corresponding discharge record (in which the glacier melt contribution was subtracted) at the *Gornera* River at *Grande Dixence* gauging station near the glacier snout for the years 2004 and 2005. Note that after July 5 2004, no lake level records were available.

We were able to observe these two different drainage mechanisms on *Gornersee*. In 2004 the flood was triggered by flotation of the ice dam and in 2005 by channel enlargement. This can be seen in the two very different lake outflow hydrographs in Figure 6.

If the flood is triggered by channel enlargement, then it is conceivable that the subglacial drainage system prevailing near the ice dam can play an important role. In 2005, it was shown with dye tracer experiments that the lake drainage initiated when the drainage system became efficient near the lake. Figure 7 shows a series of injections into a *moulin* above the lake, the transition is marked by the change in breakthrough time of the dye.

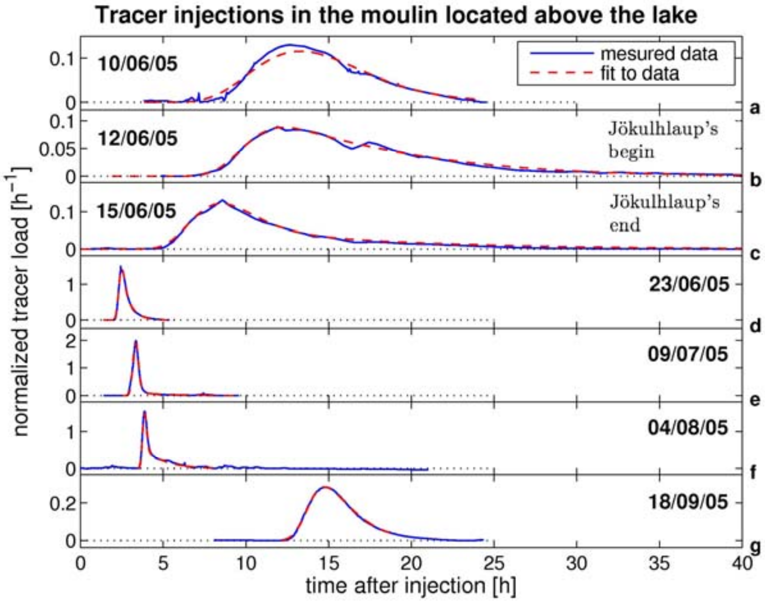

Fig.7: A series of dye tracer experiments conducted throughout the summer 2005. The *moulin* used for the injection was situated above the lake. The evolution of the drainage system from inefficient to efficient and back is marked.

During the outburst of glacier-dammed lakes, an enormous amount of lake water drains into the glacier bed within a short period and the glacier ice flow regime is expected to change drastically during a drainage event due to the changing subglacial conditions. According to the diurnal flow variations and motion events observed in the alpine glaciers so far, a sudden water input into the bed enhances the basal ice motion by increasing the subglacial water pressure. The ice flow speed significantly increases as the pressure approaches the ice overburden pressure and the glacier sole is decoupled from the bed. Because the water flux from a lake outburst is generally much larger than the meltwater input, a lake drainage may cause flow changes that are not observable under the usual hydrological conditions. Furthermore, the ice dynamics near a glacier-dammed lake are important because of their critical role in the lake drainage process. The motion of an ice dam may control the water discharge from the lake. Therefore, knowledge of glacier dynamics in the vicinity of a lake is crucial to understanding the triggering mechanisms of an outburst.

To study the impact of the drainage of a glacier-dammed lake on glacier dynamics, high frequency ice flow measurements were carried out simultaneously with hydrological observations at Gornergletscher. During the outburst event of July 2004, the flow speed increased by 100% and the surface rose by 20 cm; these processes were triggered by 4 Mill. m³ of water drained from the lake within 5 days. The water level measured in boreholes was consistently high near flotation level, suggesting that the elevated subglacial water pressure enhanced basal ice motion and subglacial water cavity formation. The most intriguing observation was that a reversred ice motion occurred, in particular, a 180° backward ice flow was recorded at one of the surveyed stakes (Fig. 8c).

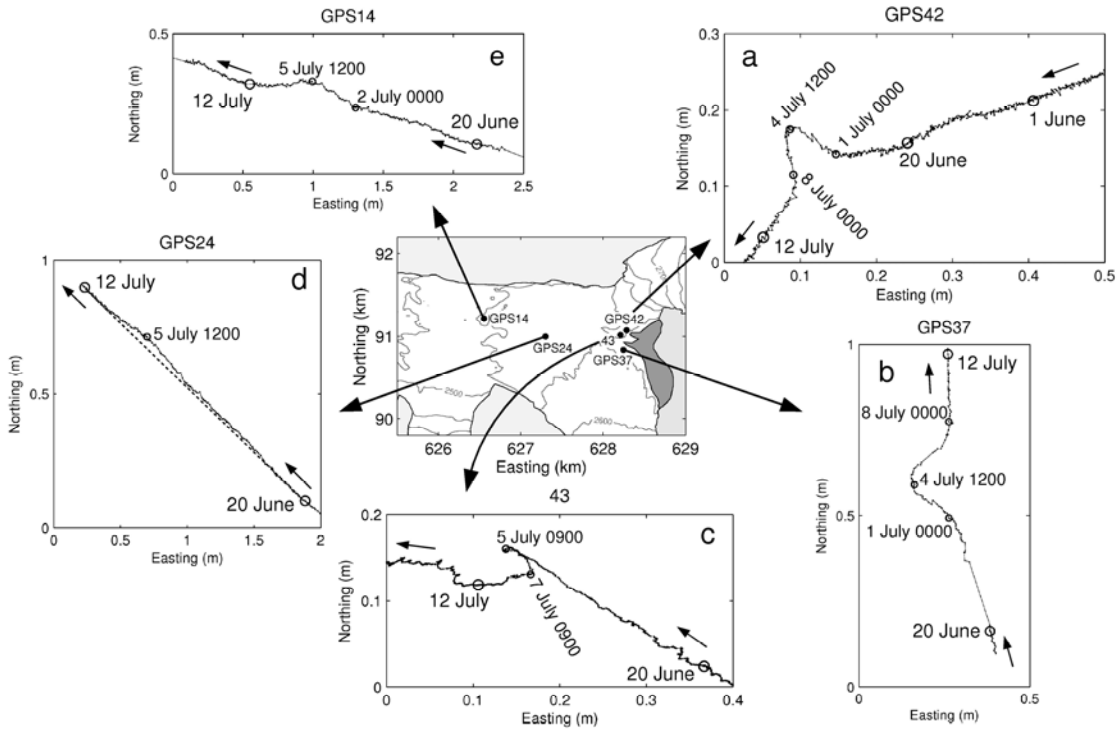

Fig. 8: Plan view of the stake motion at each survey site. The outburst began on 2 July and the water level dropped continuously until the lake emptied on July 7, 2006.

The change in flow direction was attributed to the stress coupling with the accelerated ice flow at the central part of the glacier, but its reversal was difficult to explain. A plausible interpretation is the rebound of the elastic motion of the glacier. However, Young's elasticity modulus of ice is too large to explain the observed recovery of almost the entire transverse motion, suggesting that the large-scale mechanical properties of the glacier could possibly be responsible for the elastic behavior. For example, the closing and opening of water-filled englacial fractures have the potential to change the macroscopic elasticity of the glacier system.
Because the reversal of ice motion was observed in the vicinity of the lake on the ice dam, it possibly played a key role in the triggering and the drainage mechanisms of the outburst. Moreover, the reversal was observed as being pervasive, from the lake vicinity to the lower reaches several kilometers below, implying that the phenomenon commonly occurs under the influence of rapidly changing stress conditions.

Conclusions

A detailed analysis of the data set obtained so far for *Gornergletscher* proves that a variety of different processes are involved during a lake outburst event. Our study shows the need for an integrative assessment of glacier-dammed lake floods in order to better understand the nature of these events. The dramatic dynamic response of the glacier during the lake outburst cannot be explained based on the current knowledge of glacier mechanics. Further investigations are necessary to reveal the fundamental processes triggering the initiation of a lake outburst.

Key words:

Glaciology, glacier hazards, glacier floods

Internet data bases:

http://www.vaw.ethz.ch/research/glaciology/glacier_hydraulics/gz_outburst_glacierdammed_lake

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