Glacial risk and reservoir management: the Lago della Rossa reservoir example (Valli di Lanzo, Western Alps, Italy)

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SYNOPSIS. The climatic evolution of recent years, characterised by slight winter snowfalls and very high summer temperatures, is causing a progressive loss in ice mass combined with the increase of glacial risk. Besides the widespread retreat of glaciers, one of the most evident consequences of temperature increase is the formation of epiglacial lakes, like the one formed on the left side of the Croce Rossa glacier in 1998. The glacier overhangs the reservoir of Lago della Rossa, the highest in Italy. A complete survey (GPS surveyed strain net, ablation stakes, radar echo sounding, automated air and ice temperature measurement) has been carried out since 1998 in order to establish the main features of the glacier and monitor its evolution. Mathematical and physical models have been applied in order to evaluate glacier stability and future scenarios in case of epiglacial lake outburst.

INTRODUCTION

The formation of ponds and supraglacial lakes even at an elevation higher than 3000 m a.s.l. represents one of the main consequences of the atmospheric warming which presently affects high mountain regions where glacier- and permafrost-related hazards are rapidly increasing (Mercalli et al., 2002a; Mercalli et al., 2002b; Tamburini et al., 2003; Kääb et al., in press).

Once formed, supraglacial lakes tend to expand due to thermokarst process. The appearance of a glacial lake represents a cause for concern about potential glacial lake outburst flooding (GLOF) (Mercalli et al, 2002a).

In order to either prevent or reduce the accumulation of large volumes of water and to prevent dangerous situations, practical measures have been successfully taken in many cases (pumping, syphoning, oblique drilling or tunneling through the ice body, excavation of drainage channels).

Long-term benefits and performance of dams. Thomas Telford, London, 2004

LONG-TERM BENEFITS AND PERFORMANCE OF DAMS

In 1818 at the ice-dammed Giétroz lake (Swiss Alps), despite the extreme technical and environmental conditions, a drainage tunnel about 200 m long was excavated by hand through ice (UNST, 1981; Hambrey et al., 1992).

In 1996 at the Gruben Glacier (Swiss Alps) a drainage channel was excavated in order to prevent the occurrence of outburst floods from a periglacial lake (Haeberli et al, 2001).

Drainage channels should be oriented according to the sliding direction of the glacier, in order to increase their effective life and efficiency even in cases where the speed of the glacier itself is high. Once the channel is excavated, water flowing through it rapidly melts ice and increases the width of the channel, so enhancing the excavation process.

As part of glacial lake hazards mitigation at Hualcán (Cordillera Blanca, Peru) in 1993, following installation of siphons, the construction of a 2-m diameter tunnel started. The tunnel was 155 m long beneath a rock bar below the moraine dam (Reynolds et al., 1998).

In the Himalaya remediation strategy to reduce the GLOF hazard at the Tsho Rolpa (Nepal) consisted in syphon pipes to augment the original trial pipe and an artificial spillway ((Reynolds, 1999).

DESCRIPTION OF THE INVESTIGATED AREA

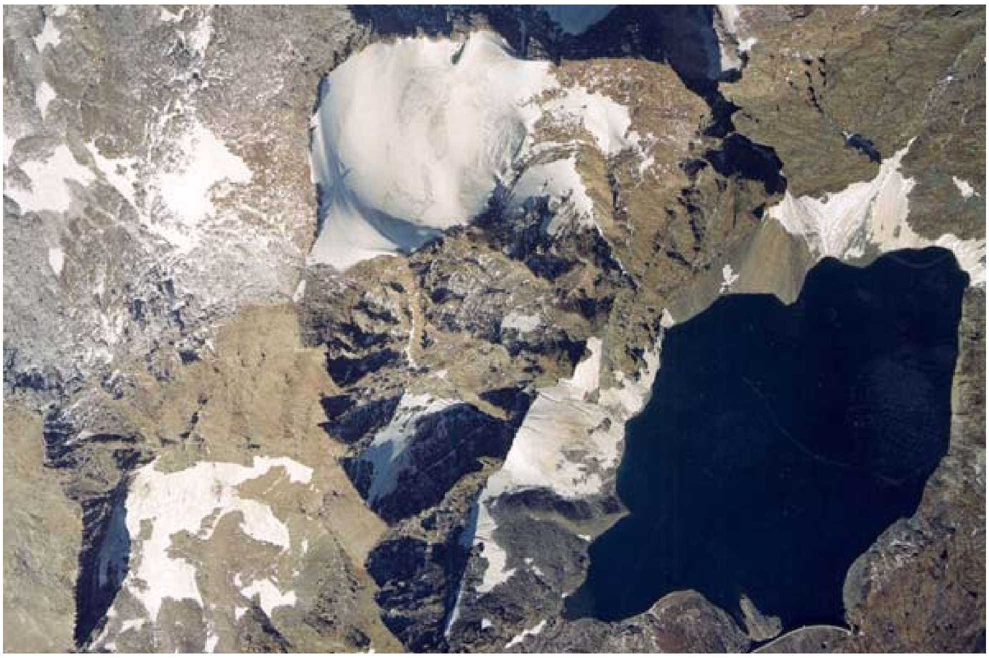

Figure 1: Aerial view of the Lago della Rossa reservoir and Croce Rossa Glacier (CNR-IRPI, 16/09/2001)

The Croce Rossa Glacier (Fig. 1 and 2) is located on the NE slope of Croce Rossa peak (3556 m a.s.l.) in Valle di Lanzo (Western Italian Alps). The steep terminus of the glacier (3380 m a.s.l.) overhangs the Lago della Rossa reservoir, the highest in Europe (2715 m a.s.l.), which is located about 700 m below.

Figure 2: The Croce Rossa Glacier (Tamburini, 05/08/2003)

In 1998 a small supraglacial lake (Fig. 3) formed near the left margin of the glacier at an elevation of about 3450 m a.s.l..

Figure 3: The supraglacial lake appeared in 1998 (Tamburini, 2000)

The presence of the supraglacial lake represents a cause for concern due to the increased risk of triggering ice avalanches into the Lago della Rossa reservoir. If waves should be generated by such events, they could seriously damage the dam and overtop the dam crest, with resulting floods in the downstream valley.
For this reason surveys were immediately carried out on the glacier in order to assess and reduce hazards and a monitoring system was installed.

STUDIES ON THE CROCE ROSSA GLACIER

The following studies were carried out in the Croce Rossa Glacier area:

- Aerial photogrammetric survey, georeferenced with GPS, provided a map at 1:2000 scale of an area including the glacier and the reservoir below
- GPS-assisted georadar surveys from glacier surface provided glacier bed morphology and glacier volume
- A physical model was performed in order to assess the water waves generated by a glacier avalanche in the Rossa reservoir

Moreover a monitoring system for the measurement of ice temperatures and glacier displacement rate has been established.

GPS-assisted GPR surveys: methodology, results and evolutive scenarios

GPS-assisted GPR (Ground Penetrating Radar) surveys from the glacier surface were carried out in December 1998 and completed in April 1999, in order to determine the ice thickness and the depth of the glacier bed. Four transverse and two longitudinal profiles were surveyed in locations determined by the glacier morphology and where access was possible.
The following equipment was used:

- GSSI SIR-2 radar system
- RADARTEAM Subecho 40 antenna, with 35 MHz base frequency
- differential GPS positioning system

Raw GPR data were processed with GSSI WINRAD Software, in order to convert the original time vs. time profiles into distance vs. depth cross sections of the glacier. A map of the glacier bed was obtained in ArcView environment, by creating and contouring a DEM (Digital Elevation Model) obtained from interpolating glacier bed elevation data. By subtracting the glacier surface and glacier bed DEMs in ArcView environment, the overall volume of the glacier and a map of the ice thickness were obtained (Fig. 4). This map was later used for physical model performance.
The most relevant results obtained by GPR investigations are listed below:

- the overall volume of the glacier was calculated as about 1.5 million m^3
- a maximum ice thickness of about 60 m was detected in the central part of the glacier

- a change in glacier bed dip, corresponding to a rather flat area in the central part of the glacier, resulted from interpolating glacier bed elevation data; such a morphological step has been considered as favouring stability of at least the upper part of the glacier (Fig. 5)

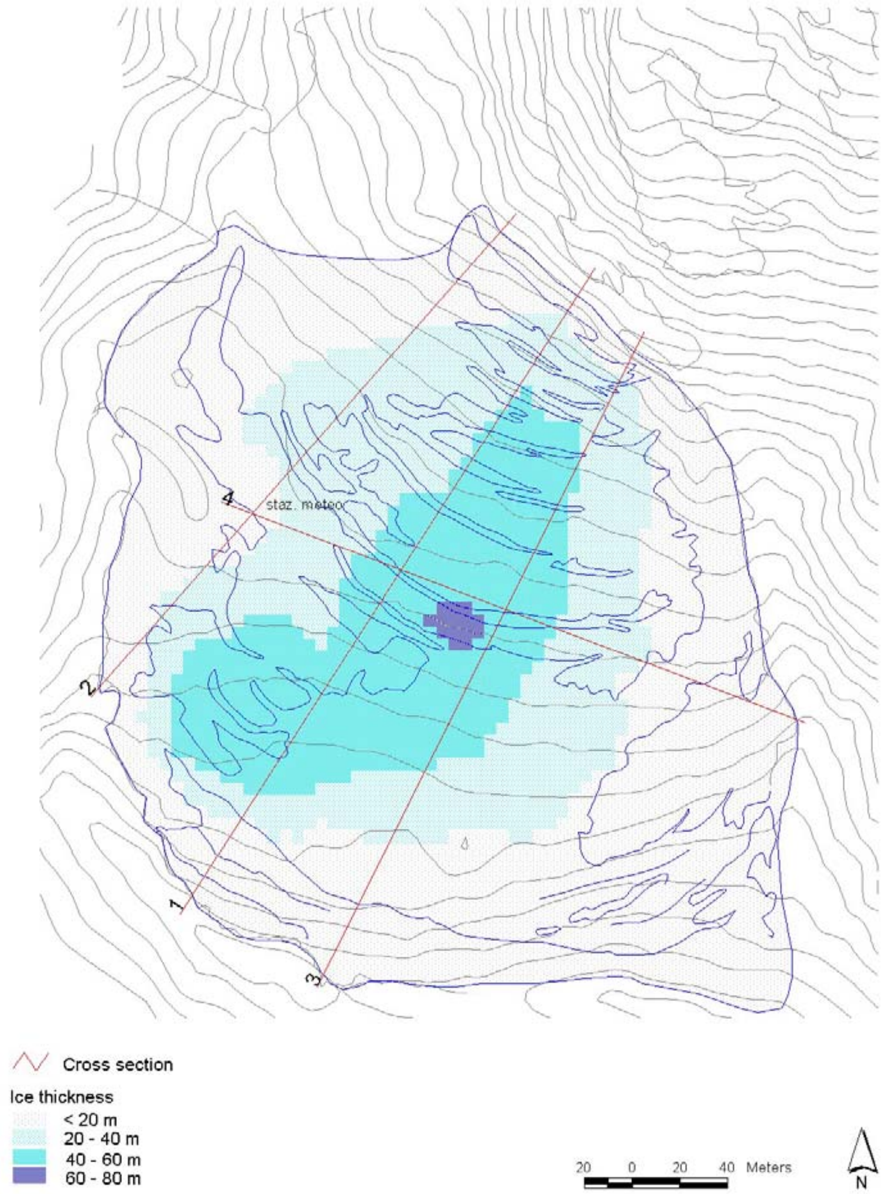

Figure 4: Ice thickness map obtained with GPR survey

Due to the morphology of the glacier bed resulting from GPR surveys, a sudden collapse of the entire glacier was considered less probable than a partial collapse in case of outburst of the epiglacial lake and subsequent sudden increase of water pressure at the base of the glacier. Considering both the major crevasse pattern and the epiglacial lake position, some hypothesis about the unstable portion of the glacier have been carried out. The worst scenario refers to the collapse of a volume of about 500,000 m^3 of ice.

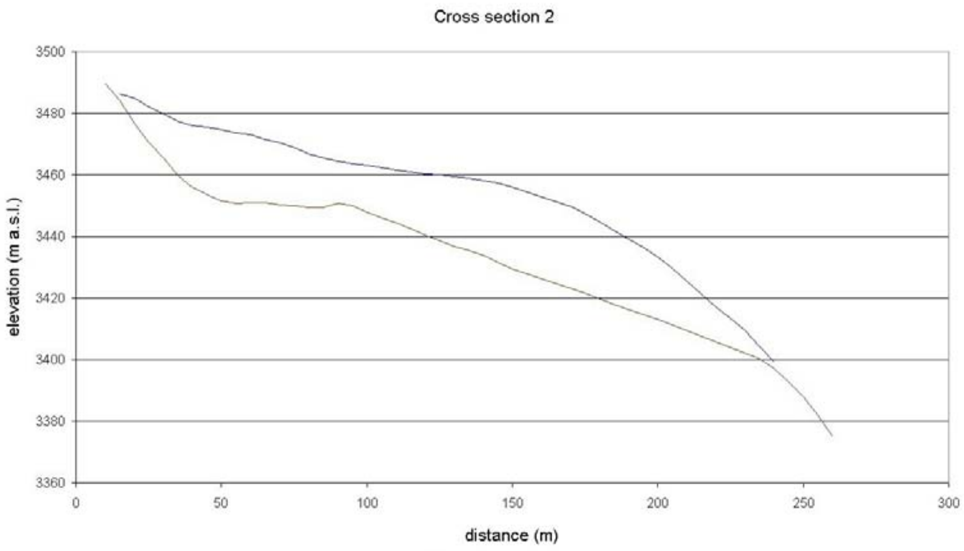

Figure 5: Longitudinal cross section of the Croce Rossa Glacier.

<u>Physical model</u>

A physical model of the glacier and the reservoir below was carried out in the Enel.Hydro labs in Milan, with the aim of assessing the water waves generated by a glacier avalanche in the Lago della Rossa reservoir (Brambilla et al., 2000). Several scenarios have been simulated, with different ice volumes and reservoir levels, in order to define threshold values for the reservoir level. The temporal development of an ice slide generated by manual and "instantaneous" removal of a gate is shown in Fig. 6.

The main results obtained by physical modelling are listed below:

- the time span occurring between the collapse and the dam overflow is lower than 1 minute
- the model provided a table of water level vs. ice avalanche volume, showing that no overflow of the Lago della Rossa dam occurs in case of collapse of an ice volume lower than 200,000 m^3
- in the worst case (500,000 m^3) only the right part of the dam top is overflown

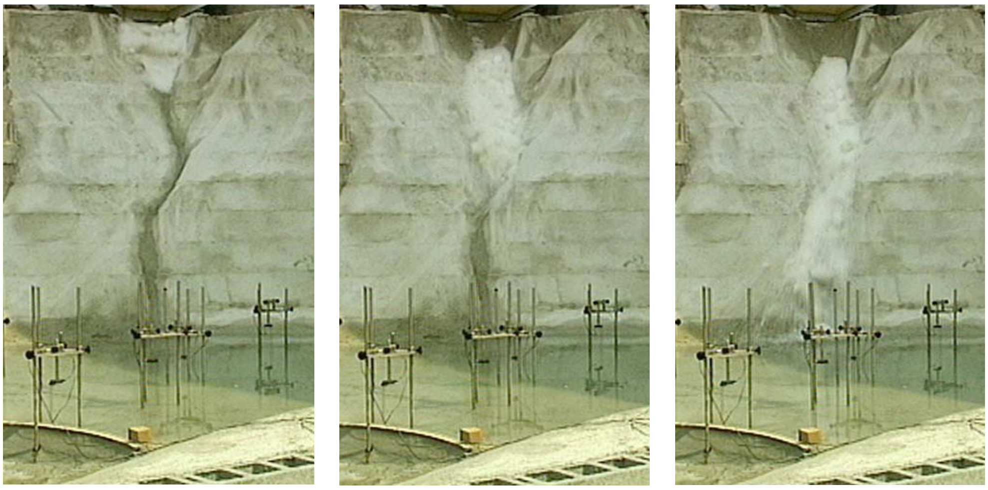

Figure 6: Temporal development of ice-slide 5, 10 and 16 seconds after the release

According to the results of the model, the maximum water level in the reservoir has been fixed 9 m lower than the maximum water level during the critical season (approximately July to September). Unfortunately, as the maximum water level is generally reached at the end of September, the above restriction represents a significant limitation on reservoir management. For this reason, appropriate measures have been proposed in order to enable a sustainable management of the reservoir itself, based on the improved knowledge of the glacier evolution acquired during about five years of glacier monitoring

MONITORING SYSTEM INSTALLED ON THE CROCE ROSSA GLACIER

The following devices were installed on the Croce Rossa Glacier:

- ablation stakes, set in holes carried out by steam drill device, provide data for mass balance and glacier sliding evaluation
- thermometers, inserted at different depths in holes, provide ice temperature measurement; both ice and air temperature data are automatically acquired and stored locally in a datalogger

Surface displacements are measured with GPS (5 stakes) and EDM (3 stakes) devices. EDM measurements are taken from the Rossa dam.

The five ablation stakes, each one formed by 5 wooden sections for a total length of 10 m, were installed in holes carried out by steam drill device. As the stakes are not visible from the below dam, static GPS measurements are regularly carried out twice a year. A GPS reference station was established on outcropping rock along the left margin of the glacier in order to simplify site operations.

Three stakes equipped with reflecting prism were installed near the glacier terminus, in order to enable glacier sliding measurement from a remote measuring topographic station from directly the below dam. Due to distance (about 1500 m) and difference in elevation (about 1000 m) traditional topographic measurements are affected by a high error, so only distance measurements can be considered reliable for the control of the glacier terminus. Distance measurements can be easily automated by using a motor driven theodolite.
Four ice thermometers were installed in holes carried out by steam drill device near the internal side of the supraglacial lake, at depths of –2, -4, -8 and –14 m respectively from glacier surface. The deepest hole reached the base of the glacier, so providing temperature values at the ice-rock contact.
A cable connection between the ice thermometer and a permanent meteorological station installed near the GPS reference station enables continuous automatic ice and air temperature measurement. The data acquisition rate is 12 per day (every 2 hours).
Mass balance is evaluated on five ablation stakes, the same used for surface movement detection with GPS measurements. Twice per year, when glacier surface displacement measurements are carried out, snow thickness, stratigraphy, density, etc. measurement are taken in order to calculate the mass balance of the glacier.
Finally, photographs of the glacier and epiglacial lake are regularly taken at least twice per year: a comparison with previous photographs allows the integration of instrumental data for an overall monitoring of the glacier evolution.

Monitoring system installation

Two programmes have been carried out in order to investigate the glacier and install the monitoring system operating at present:

- at the end of December 1998:
    - main GPR survey (completed on April 1999)
    - installation of ice thermometers at different depths, as described, with a battery powered datalogger
    - installation of ablation stakes; the stakes close to the terminus were equipped with reflecting prisms at the top, in order to enable EDM measurements from below the Rossa dam
    - installation of a reference point both for GPS and EDM measurements on outcropping rock near the left margin of the glacier
- on July 2001:
    - installation of a meteorological station at an elevation of about 3450 m a.s.l., anchored on an outcrop near the left margin of the glacier, powered by solar cells for automatic acquisition and storage of air and ice temperature data

- completion of the ablation stakes network; the stakes close to the terminus had to be replaced as they got lost

Results of glacier monitoring campaigns

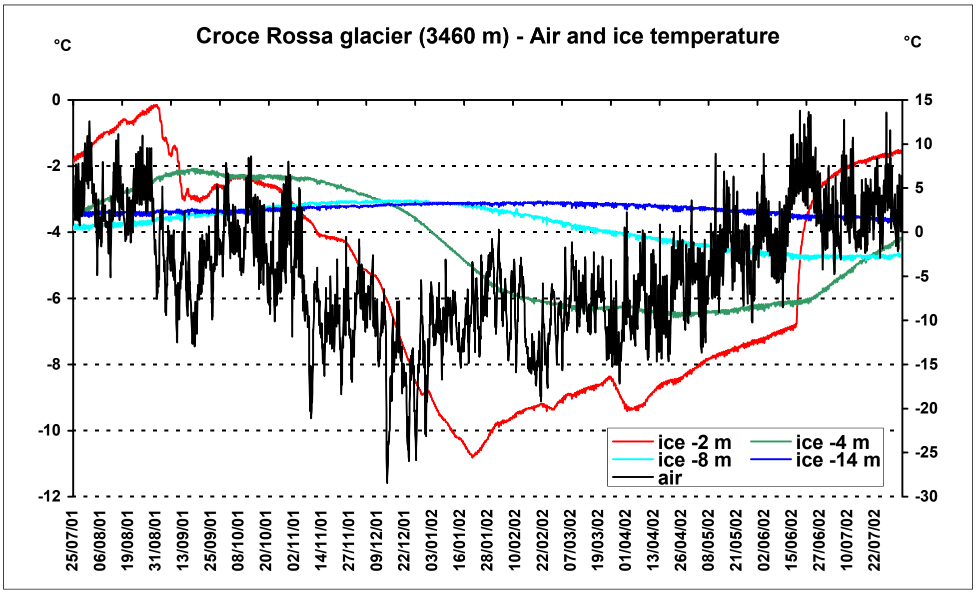

Figure 7: Air and ice temperatures recorded from July 2001 to July 2002

The glacier has been regularly surveyed for five years. The main results provided by the monitoring activity are listed below:

- the average surface planimetric displacements are about 2 m per year in the centre of the glacier, lower than 40 cm/yr near the left margin, where the thermometers are located; such values seem to be constant within the considered period (Fig. 8)
- up to 8 m of depth temperatures in ice are subject to seasonal variations; a delay in the yearly maximum value can be observed: such delay increases with depth, up to 6 months at –8 m from the surface (Fig. 7). This is in agreement with what was observed by Paterson, 1981.
- at a depth of –14 m from the surface, temperature is about constant all the year round, varying from –3.1 to –3.7 °C; this confirms that at a depth of –14 m ice is not subject to seasonal variation; moreover, the presence of a cold ice layer at the base plays an important role in increasing the glacier stability, as low temperature is responsible for the adhesion of ice to the rock below (Luthi, 1994)
- during 1998-1999 and 1999-2000 glaciological year, an intense ablation was observed; the effects of the snowy 2000-2001 winter have been observed during the following two years, characterised by a slightly positive mass balance. Finally, the exceptionally warm

2003 summer is responsible for a strongly negative mass balance (–2.5 to –3 m w.e.); the above data suggest the opportunity of performing a new photogrammetric survey, in order to calculate the overall mass reduction and upgrade the instability scenarios outlined after the first investigation programme in 1998

- water release from the terminus was never observed; this could confirm the adhesion between ice and rock at the base of the glacier, as previously observed

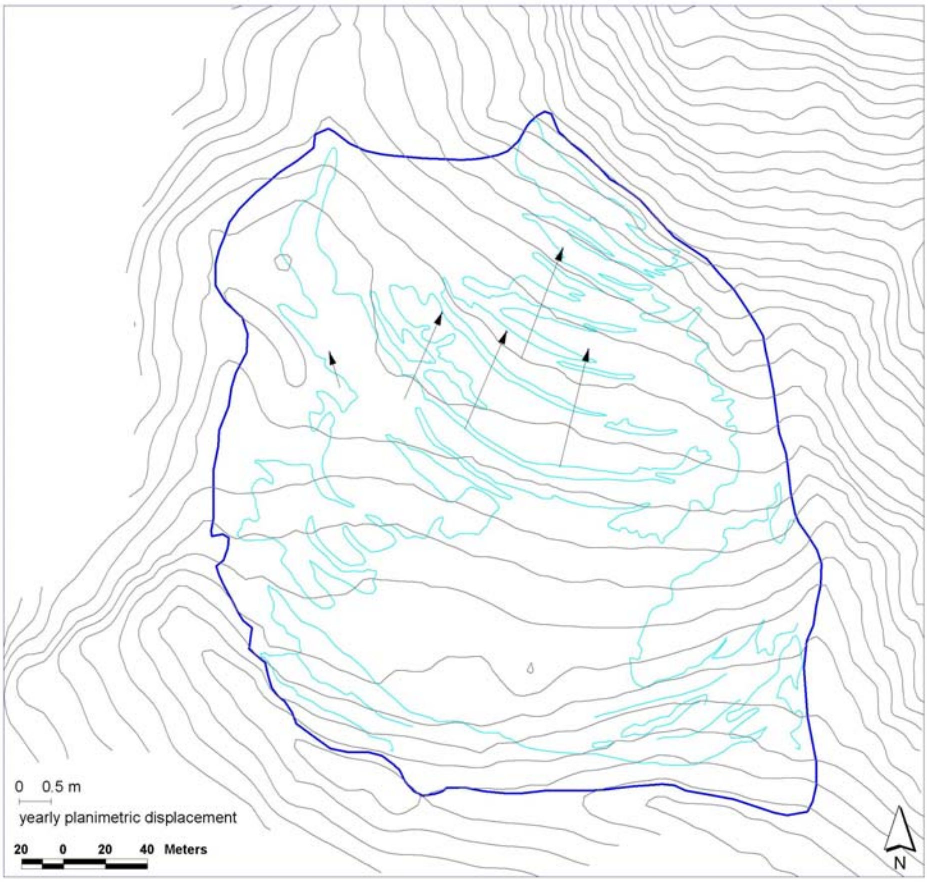

Figure 8: Yearly planimetric displacement vectors (from September 2002 to August 2003)

SCENARIOS FOR THE FUTURE

According to the results provided by monitoring, the behaviour of the glacier seems to be constant for the considered period. The dynamics of the glacier seem not to have been influenced by the high temperatures recorded during summer 2002 and 2003. Anyway, in order to verify the absence of a long term effect of the exceptionally warm 2003 summer, a further surface displacement measurement programme is progressing.

Two main collapse scenarios can be outlined for the Croce Rossa Glacier:

- sudden collapse of the lower portion of the glacier (the original volume of about 500,000 m^3 should be verified) due to outburst of the epiglacial lake and subsequent sudden increase of water pressure at the base of the glacier
- gradual increase of displacement rate at the glacier terminus before the collapse of the lower part of the glacier.

The former can be considered instantaneous, the latter can be forecast by measuring the displacement rate at the glacier terminus. In any case the main hazard is represented by water stored in the epiglacial lake, which should be removed.

FUTURE DEVELOPMENTS

In order to substantially reduce hazard and enable efficient management of the Lago della Rossa reservoir, further investigations and interventions have been planned. The main activities are listed below:

- drainage of the epiglacial lake, which could trigger an unpredictable collapse of the glacier
- performance of a new aerial photogrammetric survey, in order to evaluate the glacier volume decrease and upgrade the collapse scenarios
- set of new ice thermometers closer to the glacier terminus at different depths, including the glacier base, in order to assess the glacier stability; a proper hole must be drilled to a depth of about 50 m
- mathematical model application in order to evaluate the long term effects of increasing temperature on the glacier dynamics
- reservoir level threshold value upgrade, taking into account the reduced volume of the unstable portion of the glacier and the possibility of forecasting the collapse and the discharge of water from the reservoir in case of emergency; water level vs. time curves should be computed for different discharge rates.

To assist glacier monitoring after draining the epiglacial lake, surface displacements and temperature (air and ice) measurements should be automated, in order to enable a real time control of the glacier evolution..

Automatic EDM measurements, by means of a motor driven theodolite, should be carried out in summer and early autumn (June to October), when the reservoir level reaches its maximum and the possibility of glacier collapse is higher. In case of displacement rate increase, the application of on line Voight model approach in order to forecast the collapse time could be helpful for hazard management (Voight, 1988; Voight, 1989).

Ice and air temperature, at present automatically stored in the datalogger of the meteorological station installed of the glacier, should be transmitted by

either radio or satellite to the dam, enabling their automatic processing and comparison with threshold values.
Moreover periodic inspections on the glacier, will integrate instrumental measurements and provide data for mass balance evaluation.

CONCLUSIONS

The results of the studies carried out on the Croce Rossa Glacier and the data collected by the monitoring system during the last five years showed that:

- the main cause for concern is represented by the supraglacial lake, which must be drained in order to eliminate the main cause of sudden collapse of the lower portion of the glacier
- mass balance results showed that the overall volume of the glacier has been significantly reduced
- ice temperature values indicate the presence of a cold ice layer at the base of the glacier, which plays an important role in increasing the glacier stability
- the sliding velocity of the glacier is known and seems to be constant during the considered period, with a maximum of 2 m per year in the central part; an increase in sliding velocity can be identified if an automatic monitoring system is operating during the critical season (June to September).

Once the supraglacial lake has been drained, an automatic monitoring system, based on displacement and ice temperature measurement, will enable the possibility to manage the reservoir, according to what happens in other similar situations in the Alps, like the Jungfrau railway below the Eiger Glacier or the Mauvoisin dam below the Giétroz Glacier (UNST, 1981; Luthi, 1994)

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