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## GIS ANALYSIS OF RUTOR GLACIER (AOSTA VALLEY, ITALY) VOLUME AND TERMINUS VARIATIONS

**ABSTRACT:** VILLA F., DE AMICIS M. & MAGGI V., *Gis analysis of Rutor Glacier (Aosta Valley, Italy) volume and terminus variations*. (IT ISSN 1724-4757, 2007).

Glaciers are an important economic and natural resource to be protected. It is important to develop new techniques for surveying and monitoring glacial bodies that are generally and rapidly retreating due to present climate conditions linked to global warming. Terminus variations in Italian Alpine Glaciers are traditionally determined yearly by measuring the distance between the terminus and ground control points.

Thanks to new technologies and digital cartography, it is possible to generate and manage accurate glacier models that can integrate data time series to obtain more detailed views.

Variations in the surface area and volume of Rutor Glacier (Val d'Aosta), from its maximum expansion in the Little Ice Age to the present, ongoing retreat, were determined through a combination of ground surveys, digital techniques and pre-existing data time series. From the mid-19<sup>th</sup> century to 2004 the glacier terminus retreated 2 km, but there is evidence for two different cold periods of glacier advance. Furthermore, the glacial retreat that began again in 1990 seems to be faster than that of previous periods of recession. Rutor Glacier lost about 480 million cubic meters of ice between the Little Ice Age and 1991.

Morphologic and volumetric analyses indicate that in the last decades Rutor Glacier has lost large quantities of ice mass with no significant terminus retreat (-46 million cubic meters of ice against - 1.4 hectares of areal extension with respect to the total surface area of 911 hectares); the glacier has gradually thinned while maintaining an almost constant surface area. The Equilibrium Line Altitude changed from 2775 m in the Little Ice Age maximum to 2850 m in 1991, for a total increase of 75 m.

**KEY WORDS:** DEM, GIS, Glacier variation, Volume variation, Rutor Glacier (Aosta Valley, Italy).

**RIASSUNTO:** VILLA F., DE AMICIS M. & MAGGI V., *Analisi delle variazioni volumetriche e frontali del ghiacciaio del Rutor (Val d'Aosta, Italia) attraverso l'utilizzo di GIS*. (IT ISSN 1724-4757, 2007).

I ghiacciai sono un'importante risorsa economica e naturalistica da proteggere. Conseguentemente alle condizioni climatiche attuali, legate al

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riscaldamento globale in atto, è utile sviluppare nuove metodologie di analisi e monitoraggio dei corpi glaciali, che stanno subendo un generale e rapido regresso. Tradizionalmente, le osservazioni sulle variazioni frontali dei ghiacciai Alpini Italiani è condotto tramite misurazione della distanza tra la fronte ed alcuni punti di controllo sul terreno. Grazie alle nuove tecnologie ed alla digitalizzazione della cartografia è oggi possibile generare e gestire accurati modelli delle superfici glaciali, che, se integrate con le serie temporali ed i monitoraggi classici, possono fornire una visione più dettagliata dell'evoluzione di un ghiacciaio.

In questo lavoro sono state calcolate le variazioni frontali e volumetriche del ghiacciaio del Rutor (Val d'Aosta) dalla sua massima espansione nella Piccola Età Glaciale al 2004, utilizzando serie temporali persistenti, rilievi di campo e tecniche digitali, ricostruendo in tal modo la storia del suo regresso, attualmente ancora in corso.

Dalla metà del XIX secolo al 2004 il Rutor ha subito un regresso frontale di circa 2 km, intervallato da due periodi «freddi» di avanzata. Inoltre, dagli Anni '90 è iniziata l'ultima fase di regresso, che sembra essere molto più rapida delle precedenti. Tra la sua massima espansione nella Piccola Età Glaciale ed il 1991, il ghiacciaio del Rutor ha perso 480 milioni di m<sup>3</sup> di ghiaccio.

Le analisi morfologiche e volumetriche hanno portato a dimostrare come negli ultimi decenni il ghiacciaio abbia perso grandi quantità di massa, senza però far registrare un parallelo regresso frontale (-46 milioni di metricubi di ghiaccio, contro una diminuzione areale di 1,4 ettari, su una superficie totale di 911 ha); mantenendo costante la sua superficie, il Rutor ha infatti subito un generale assottigliamento. La quota della Linea di Equilibrio si è spostata da 2775 m nella Piccola Età Glaciale a 2850 m nel 1991, con una variazione di 75 m.

**TERMINI CHIAVE:** DEM, GIS, Variazioni glaciali, Variazioni volumetriche, Ghiacciaio del Rutor (Val d'Aosta, Italy).

### INTRODUCTION

According to the World Glacier Inventory database (<http://nsidc.org>), on the Italian side of the Alps there are about 1500 glacial bodies with different dimensions (only 130 of these are bigger than 1 km<sup>2</sup>) and covering an area of about 800 km<sup>2</sup>.

Glaciers are of major importance in the alpine environment for their natural and economic value. They represent an economic resource for mountain communities whose economy is based on tourism. They also store

freshwater, recharging in the winter season and releasing water in the summer, acting as regulators for the recharge of artificial basins that produce electricity. Furthermore, since they can affect morphology, microclimate and water regimes, glaciers can be the cause of natural disasters.

Italian glaciers are traditionally monitored through annual measurement of the terminus distance from ground control points and through strain-net networks. These analyses yield point data which must be extrapolated to the rest of the glacier. Since 1913 the Italian Glaciologic Committee makes this type of analysis and publishes results yearly in its Bulletin. A complete view of the glacial area is represented on topographic maps that are updated roughly every 10 years (1:10,000 CTR maps) or 20-25 years (1:25,000 IGM maps). Cartographic data may therefore be used to study the evolution of glaciers only in relation to the few years in which the air photogrammetric survey was completed.

New technologies and digital cartography enable the production and handling of vector data, thus allowing a different approach to this kind of investigation. Vector data can be used to directly quantify surface and volume variations.

Aerial photos and satellite images represent another kind of data which allow the analysis of glacier extension and the development of models of glacier morphology. The use of Geographic Information Systems (GIS) enables a more comprehensive handling of territorial data than tra-

ditional methods, allowing different kinds of processing and the rapid and inexpensive comparison of results. We here present the reconstructed evolution of Rutor Glacier from the Little Ice Age to the present day.

## STUDY AREA

Rutor (or Ruitor) Glacier is located in the Rutor Massif, in La Thuile the Valley (or Rutor Valley) within the Val d'Aosta Region of northern Italy (fig. 1). Its surface area of more than 8.5 km<sup>2</sup> makes it one of the ten biggest glaciers in the Italian Alps. It has a mainly north-west aspect, with an approximately rectangular shape and low slope, even if there is an evident ice fall near the «Vedette del Rutor». Its basin is bound to the south-west by the French/Italian border, to the south by Testa del Rutor peak and the Saint Grat Dessus and Moriond Dessus glaciers, to the east by the Doravidì group, Tsassè Blanc Glacier, and Flambeau and Invergneures glaciers, and to the west by the Grande Assaly Glacier.

Rutor Valley is characterised by many lakes that occupy the cavities left by retreating glaciers and are mainly filled by glacial sediments and glacial meltwater. Meltwaters also feed the Rutor Torrent, which forms the three cascades that can be admired along the path leading to the Deffeyes mountain hut.

Rutor Glacier is sadly famous for the catastrophic floods of the S. Margherita marginal lake which have oc-

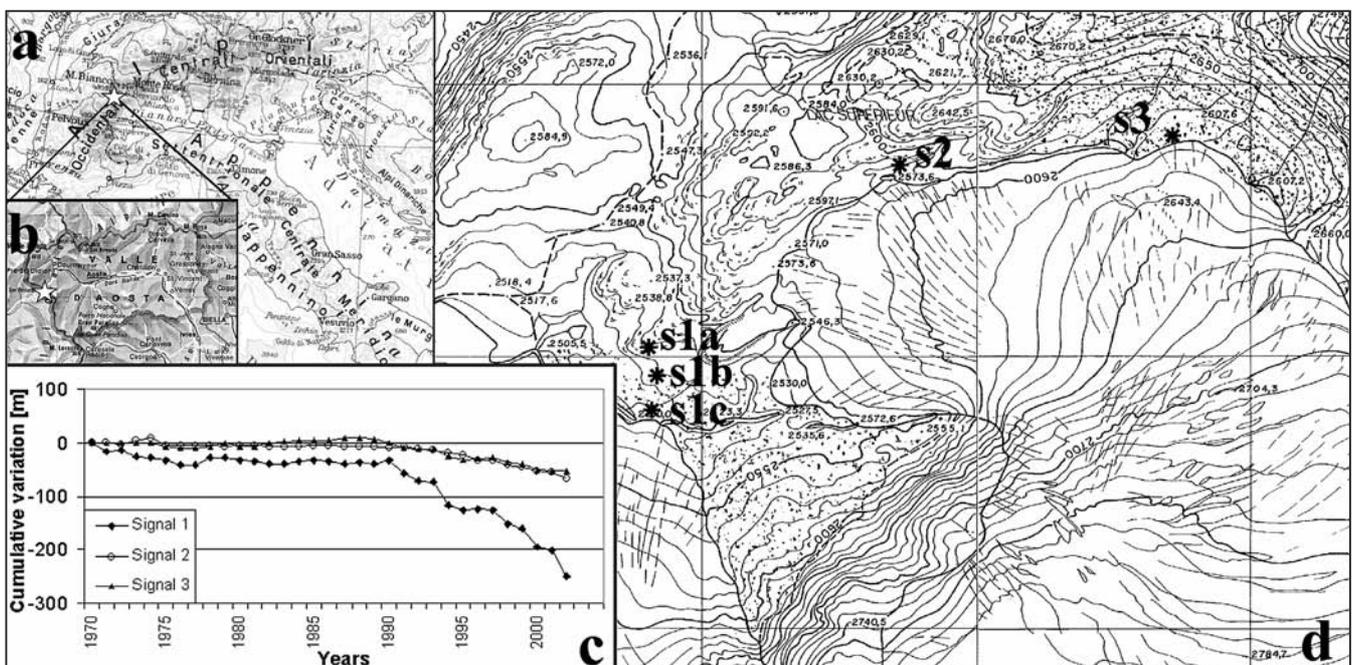


FIG. 1 - Rutor Glacier: geographic location (1a, 1b) and cumulative variations in its terminus in the 1970/2002 time interval (1c). The terminus shows a retreat of 50 meters in at signals number 2 and 3, while its retreat was four times greater at signal number 1. Signal positions are shown in map 1d, where: s1a, s1b, s1c are the positions of signal 1 respectively in 1970, 1982, 1991; s2 is the position of signal 2; s3 is the position of signal 3.

curred repeatedly since 16<sup>th</sup> century, when the glacier barring the west side of the lake was no longer able to hold the water pressure. Some reports of these catastrophic events (Baretti M., 1880) were used to further constrain glacier reconstructions.

## ANALYTICAL METHODS

This work integrated GIS processing with traditional survey methods. Traditional surveys were mainly used to analyse terminus and surface variations, while GIS processing was used to determine volume variations.

Data from the Bulletin of the Italian Glaciological Committee, terminus reconstructions in literature, digital cartography and ground surveys were all used to reconstruct the evolution of the glacier from its maximum extension in the Little Ice Age to the present day. There are two different kinds of digital cartographic data:

- Digital maps created by scanning cartography (raster data). The number and size of pixels determine the image resolution.
- Geographic representations, where data are represented as georeferenced points, lines and polygons (vector data). Every single feature can be linked to one or more attributes. Almost every type of raster data can be transformed into vector data through digitising. This kind of data, generally already georeferenced, can be easily acquired and manipulated using GIS software (i.e. ArcView or IZWIS). The big advantage is that vector data contain some information that can be analysed immediately. For example, it is possible to generate a Digital Elevation Model (DEM) directly from vector contour lines; in glacier areas contours (reported in all cartographic maps) represent the morphology of the glacial body itself, thus allowing the analysis of morphological variations every time new cartography is published.

A DEM is a representation of the morphology of an area; an elevation value is associated with every DEM pixel area. By knowing the DEM pixel area, it is possible to analyse the difference in elevation pixel by pixel, and to estimate glacier volume and morphological variations. Furthermore, it is possible to derive slope and aspect maps directly from the DEM. The use of DEMs as a tool for morphologic analysis raises some conceptual issues. DEMs are a matrix of values and not a continuous surface (i.e. they can be considered regularly sampled points), and the pixel size is of fundamental importance to every analysis.

In this kind of approach it is very important to know the accuracy of vector data, since any error is introduced in subsequent processing steps. The accuracy of the final output depends on the accuracy of base cartography and on the interpolation algorithm used to generate the DEM.

Three types of cartography were used in this study:

- Hand-digitised, 1975 Technical Regional Cartography (CTR) at a 1:10'000 scale, with a planimetric accuracy of 4 m and an altimetric accuracy of 1.8 m for ground control points and of 3.5 m for contour lines (Commissione Geodetica Italiana, 1973).
- 1991 Vector Technical Regional Cartography (CTR) at a 1:10'000 scale: its accuracy is no lower than that of the 1975 CTR maps (although the graphic error in vector cartography can not be measured, the precision of vector data is greater than that of raster data).
- Contour line reconstruction of the maximum extent of the Little Ice Age. Since the reconstruction, based on guidelines published by Porter (1975), was subjective, it is difficult to measure accuracy. Porter himself states that the altimetric error in this kind of reconstruction is less than 50 m, and the error for small glaciers such as Rutor Glacier is surely much smaller.

TABLE 1 - Calculated errors in the elevation models

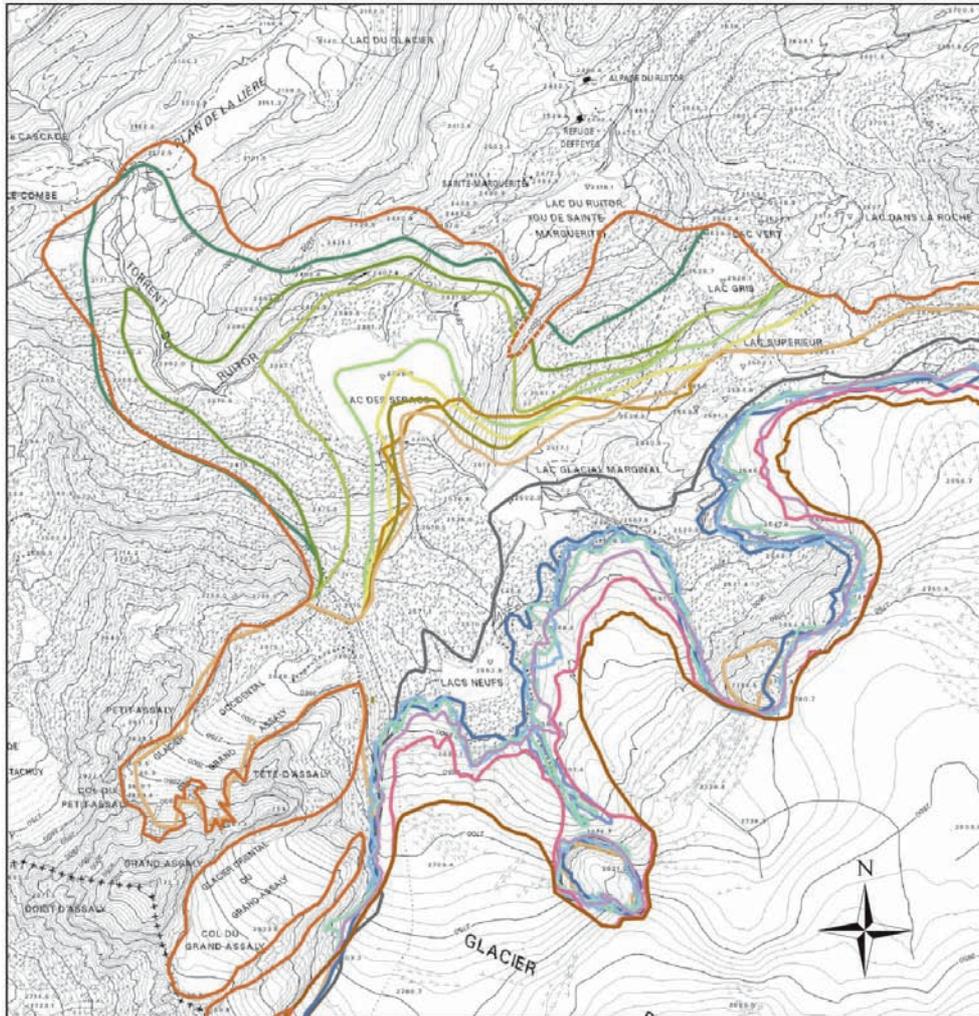
	LIA contour lines reconstruction	CTR 1975	CTR 1991
Contour lines altimetric rms error	20 m (estimated)	1,7 m	1,7 m
2 m pixel DEM rms error	No data	2,674 m	3,659 m
5 m pixel DEM rms error	No data	2,641 m	3,938 m
10 m pixel DEM rms error	No data	2,931 m	5,066 m
2 m pixel DEM systematic error	No data	0,877 m	1,765 m
5 m pixel DEM systematic error	No data	0,752 m	1,838 m
10 m pixel DEM systematic error	No data	0,773 m	2,198 m

## TERMINUS AND SURFACE VARIATIONS

The glacier perimeter in 15 different years was reconstructed using cartography, terminus reconstructions by different authors since the second half of the 19<sup>th</sup> century, orthophotos and ground surveys. Figure 2 shows these limits superimposed on the 1991 cartography.

The Rutor Glacier terminus perimeters of 1864, 1873, 1879, 1905 and 1916 were drawn in a 1917 reconstruction (Sacco, 1917) and in an article published in 1934 (Sacco, 1934). M. Bossolasco published a planimetry of the 1926 terminus (Bossolasco, 1928), while Peretti publishing a map of the 1933 glacier terminus (Peretti, 1934).

The 1930 and 1968 perimeters were drawn on IGM cartography (IGM plate: 28 III SO «La Salle» and 41 IV NO «Valgrisanche» at a 1:25,000 scale).



**Legend**

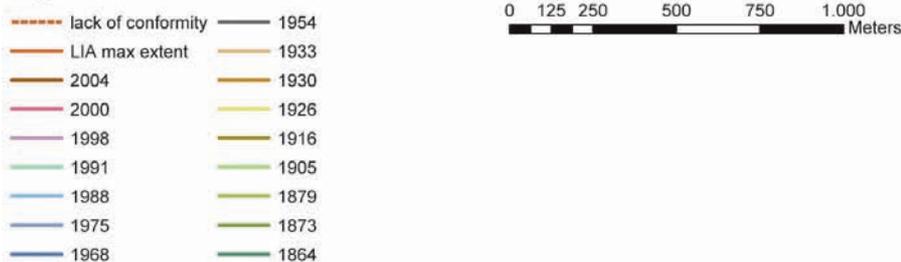


FIG. 2 - Reconstruction of the terminal portion of Rutor Glacier from its maximum extent in the LIA to 2004. The 1864, 1873 and 1879 limits, sketched by Sacco, locally disagree with the field survey by Orombelli.

The 1975 and 1991 perimeters were drawn on Aosta Valley 1:10,000 Technical Regional Cartography. The 1954 and 1988 perimeters were drawn on orthophotos. The terminus was mapped in a 1998 topographic field survey (Parigi, 1999). The most recent 2000 and 2004 perimeters derive from orthophotos and GPS surveys, respectively.

The maximum extent of the glacier in the Little Ice Age (about 1820) was reconstructed during a field survey in Summer 2004 (Orombelli, 2005).

The maximum extent of the Rutor Little Ice Age (LIA) is represented in fig. 4. These cartographic data have been georeferenced and completed, where necessary, for the higher areas of the glacier perimeter, keeping the external limits of the accumulation basin constant.

Data from the Italian Glaciological Committee Bulletin were analysed for the years after 1970 (Boll.CGI - serie 1, serie 2, serie 3 - years 1914-2001).

Starting from 1971 there are three time series for Rutor Glacier; these are referred to three ground signals located

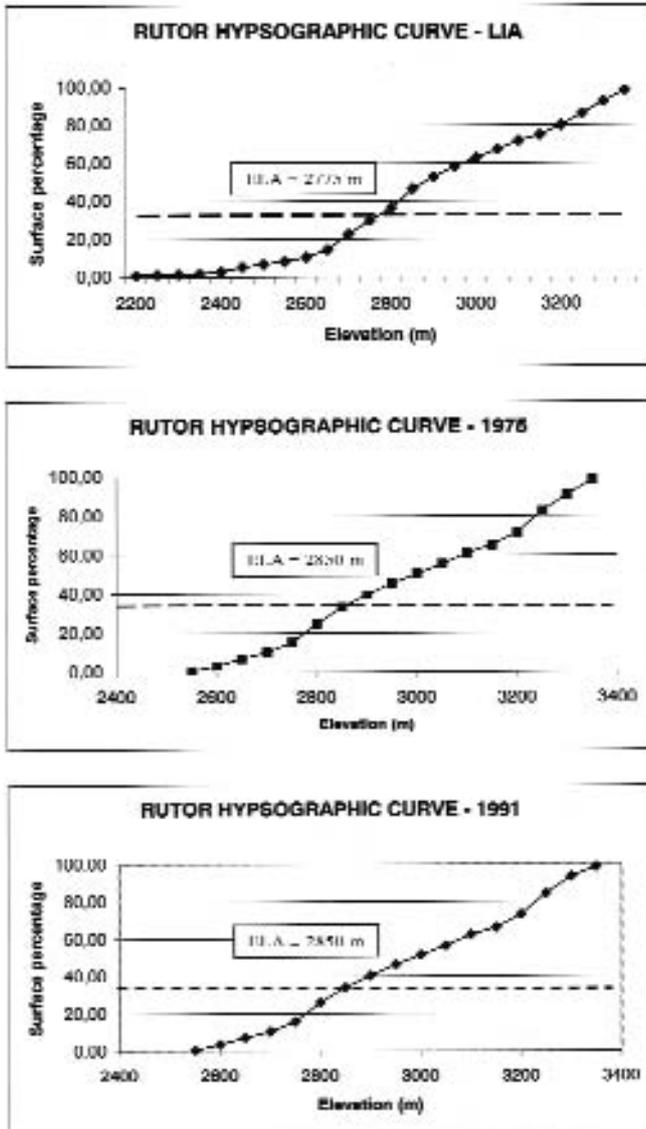


FIG. 3 - Rutor Glacier hypsographic curves for LIA maximum extent, 1975 and 1991. The dashed line represents 33.3% of the glacier surface, which corresponds to the Equilibrium Line Altitude on the horizontal axis.

close to the terminus (fig. 1). Each year the series indicate the distance from these signals to the terminus. The Rutor terminus was apparently stable between 1970 and 1990, with a weak advance ending in 1986, followed by an evident retreat that was more pronounced in the western part of the glacier. This small advance in the Eighties is also known in many other Alpine glaciers, in accordance with the climatic time series.

The linear retreat of the terminus from the maximum extent of the LIA to 2004 was of 2 km; this was interrupted by a «cold» period of advancement between 1916 and 1926 and a second, less intense one between 1975 and

1988. These data agree with climate records and with the general behaviour of Alpine glaciers.

A quantitative study of Rutor Glacier surface variations was carried out using the reconstructed perimeters; results are shown in tab. 2. Rutor Glacier has lost 31% of its surface area, which was almost 1300 ha during the Little Ice Age but was little more than 850 ha in 2004.

TABLE 2 - Rutor glacier surface variation between maximum olocenic extent and 2004. In the graphic it is possible to observe the two glacial advances (about 1920 and about 1986). It is noticeable that the curve slope seems to be gradually increasing and, in particular, the retreat trend started in the Nineties seems to be much faster than the former ones

Year	Surface Area	Variation %	Cumulative variation %
LIA	12'471'698,23 m <sup>2</sup>	-	-
1864	12'251'025,23 m <sup>2</sup>	-1,77%	-1,77%
1873	11'813'819,73 m <sup>2</sup>	-3,57%	-5,27%
1879	11'542'262,23 m <sup>2</sup>	-2,59%	-7,45%
1905	10'757'927,08 m <sup>2</sup>	-6,71%	-13,74%
1916	10'612'557,58 m <sup>2</sup>	-1,22%	-14,91%
1926	10'645'864,77 m <sup>2</sup>	+0,25%	-14,64%
1930	10'529'835,08 m <sup>2</sup>	-0,97%	-15,57%
1933	10'471'447,68 m <sup>2</sup>	-0,56%	-16,04%
1954	9'420'253,98 m <sup>2</sup>	-10,04%	-24,47%
1968	9'207'522,64 m <sup>2</sup>	-2,26%	-26,17%
1975	9'125'099,77 m <sup>2</sup>	-0,86%	-26,83%
1988	9'202'909,52 m <sup>2</sup>	+0,85%	-26,21%
1991	9'110'951,94 m <sup>2</sup>	-1,00%	-26,95%
1998	9'076'623,29 m <sup>2</sup>	-0,35%	-27,22%
2000	8'794'609,94 m <sup>2</sup>	-3,19%	-29,48%
2004	8'569'761,69 m <sup>2</sup>	-2,61%	-31,29%

## VOLUMETRIC VARIATIONS

Rutor Glacier volumetric variations were determined pixel-by-pixel by differencing DEMs for different years. Although this method can be used to quantify the volume of ice lost between two periods in every single area represented by a pixel, it does not provide any information on the whole volume of the glacier. The glacier bedrock morphology must be known to obtain the latter kind of data. No such data are available for the bedrock of Rutor Glacier.

A DEM can be generated from vector contour lines: GIS tools may be used to rasterise contour lines and then apply an interpolation algorithm which assigns an elevation to every pixel. Three DEMs were produced. The first, showing the maximum extent of the LIA, is based on contour lines reconstructed using Porter's methodology: contour lines were drawn every 50 meters, linking points with the same elevation and situated on opposite sides of the perimeter. Contour lines were drawn progressively more convex or more concave moving respectively downslope or upslope of the Equilibrium Line Altitude.



FIG. 4 - The surface and topography of Rutor Glacier at its maximum extent in the Little Ice Age. Glacier contour lines are drawn with a 50 m interval.

The 1975 DEM was produced by hand-digitising contour lines from CTR raster cartography. The 1991 DEM was produced using CTR vector cartography. A prerequisite for analysing the difference between two DEMs is that the models can be overlapped, i.e. they must have the same pixel size and be georeferenced to the same coordinate system.

Pixel size, one of the most important parameters in DEM interpolation, is user-defined. We chose to use a 2 m, 5 m and 10 m pixel grid for 1975 and 1991 DEMs, which derive from cartography with 10 m contour intervals. The 2 m grid was not applied to the LIA DEM because the required accuracy was not consistent with the 50 m contour interval.

Tables 3 and 4 show volumetric variations in Rutor Glacier for the following time intervals: 1975-1991, LIA-1975 and LIA-1991. There are no significant differences between results obtained for different pixel sizes, although smaller pixel sizes tend to detect smaller variations. It is difficult to attribute the latter effect to any one factor: it is most likely determined by a «step effect» which increases with the pixel size, thus creating an even bigger difference.

TABLE 3 - Rutor Glacier volume variations between 1975 and 1991. Measurements were made using different pixel sizes

Pixel size	Volume variation
100 m <sup>2</sup>	-46'348'900 m <sup>3</sup>
25 m <sup>2</sup>	-46'135'508 m <sup>3</sup>
4 m <sup>2</sup>	-46'065'032 m <sup>3</sup>

TABLE 4 - Rutor glacier volume variations in the LIA/1975 and LIA/1991 time intervals. The difference between these two variations does not agree with the difference between 1991 and 1975 DEMs. This is due to cartographic and interpolation errors in the present deglaciated area, which were not considered in the 1991-1975 analysis

Pixel size	Peg/1975	Peg/1991
100 m <sup>2</sup>	-427'158'810 m <sup>3</sup>	-480'226'060 m <sup>3</sup>
25 m <sup>2</sup>	-427'119'363 m <sup>3</sup>	-480'293'995 m <sup>3</sup>

Besides the quantitative aspects of analysis, the morphologic evolution of the surface is also very interesting. Between 1975 and 1991, the surface area of Rutor Glacier did not change significantly (0.16%); its terminus did not retreat substantially, as confirmed by data from the Geological Committee Bulletin.

This almost stationary state in the area is not reflected in a near-zero mass balance. Although the glacier is not retreating substantially at its terminus, it has undergone a general thinning with consequent mass loss. This is probably the effect of glacier mass re-equilibration after a period of positive mass balance in the Eighties. In particular, there is a strongly negative mass balance and a 40 m decrease in elevation in a wide south-eastern portion of the accumulation basin close to a western portion with a positive mass balance. Analysis of aerial photos show that these anomalies are due to errors in the 1975 cartography; the south-eastern part of the accumulation basin was probably reconstructed from a series of aerial photos taken on a cloudy day.

In the terminus area there is evidence of greater thinning in the eastern tongue than in the western one.

The LIA DEM - 1975 DEM and LIA DEM - 1991 DEM values are in accordance with the general dynamics of the glacier: there is a general loss of mass, which is especially evident at lower altitudes corresponding to the present deglaciated areas. The difference between DEMs for the described time intervals are shown in figs. 5a and 5b (the LIA-1991 difference is not reported because it is graphically very similar to the LIA-1975 difference). We compared DEMs of deglaciated areas near the Rutor Glacier terminus from different periods to evaluate the accuracy of results. The deglaciated areas should not show altimetric variations in the considered interval of time.

Three areas were selected. The first area is the entire territory freed by the LIA-1975 glacier retreat, while the two other areas are selected portions of this territory that exclude zones (e.g. very high or low slopes, lakes) which are not statistically significant.

The altimetric difference measured in these areas using the 1975 and 1991 DEMs shows a Gaussian distribution of data not centred on zero, as expected. A mean decrease in altitude of two meters cannot be attributed to any natural phenomena but to cartographic errors.

Volumetric variations in the 1975-1991 time interval were corrected to extend this result to the entire glacier area: mass loss was found to be 27'756'095 m<sup>3</sup> (the mean of values obtained for different pixel sizes). The correction suggested is quite big, but it is in accordance with the accuracy calculated for the surface models. Rutor Glacier thinning between 1975 and 1991 has been detected by the proposed method, but the calculated values are close to the method accuracy. Even if the quantitative values have an error that is high in percentage, this models provide good informations for the morphological analysis. Volumetric variations were also measured using the method proposed by Haeberli & Hoelze (Haeberli & Hoelze, 1995), which determines the volume of a glacier body based on four input parameters: surface area, maximum length, minimum altitude and maximum altitude.

The volume of Rutor Glacier was modelled for the 17 years in which the perimeter is known (tab. 5). DEM-based volume variations and Haeberli model-based volume variations agree in the LA-1975 time interval, but not in the 1975-1991 time interval.

The two measured variations in the LIA-1975 period differ by almost 130 million cubic meters (26% of the total variation). Considering the simplicity of both the model and the LIA reconstruction, this is an acceptable result.

The data for the 1975-1991 time interval are more interesting: the Haeberli model measures a volumetric ice loss of 3'681'173 m<sup>3</sup>, whereas the DEM-based volumetric difference is 46'183'147 m<sup>3</sup> (27'756'095 m<sup>3</sup> when corrected for cartographic errors).

This huge volumetric difference can be explained considering the variations in the morphology of Rutor Glacier: in this period the glacier lost mass from its entire surface, with no relevant change in surface area or length.

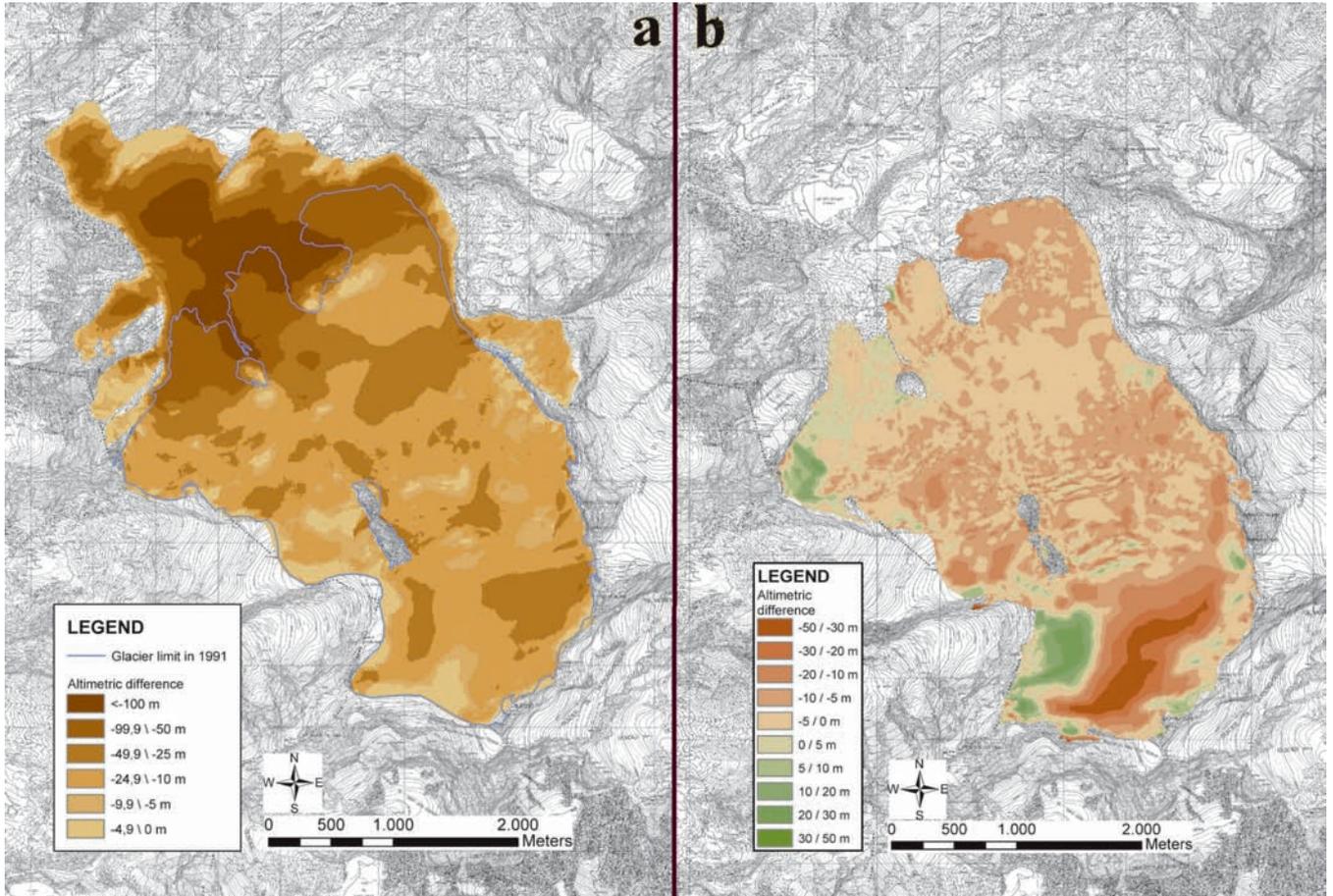


FIG. 5a - Altimetric difference between the LIA DEM and the 1975 DEM. Pixel size: 5 m. The 1991 glacier limit is indicated in blue. The brown area represents the Little Ice Age glacier tongue with an ice thickness of about 100 m, now completely melted.

FIG. 5b - Altimetric difference between the 1975 DEM and the 1991 DEM. Pixel size: 5 m. The planimetric extent of the glacier in 1991 was very similar to that in 1975, and has not been drawn on the map. It is evident where cartographic errors are (red and green areas in the accumulation basin); except for these areas the mass loss is less evident near the glacier terminus: this is probably due to a re-equilibrium of mass from the accumulation basin to the ablation basin after the glacial advance in the Eighties.

TABLE 5 - Rutor Glacier volume measured through the W. Haerberli model. The glacier volume, the water equivalent volume, and the percentage of variation are reported for each year

Year	Volume	Volume W.E.	Variation %
LIA	890'587'086 m <sup>3</sup>	810'434'248 m <sup>3</sup>	-
1864	875'804'198 m <sup>3</sup>	796'981'820 m <sup>3</sup>	-1,66%
1873	824'417'125 m <sup>3</sup>	750'219'584 m <sup>3</sup>	-5,87%
1879	795'133'997 m <sup>3</sup>	723'571'938 m <sup>3</sup>	-3,55%
1905	720'556'250 m <sup>3</sup>	655'706'188 m <sup>3</sup>	-9,38%
1916	689'111'085 m <sup>3</sup>	627'091'087 m <sup>3</sup>	-4,36%
1926	700'209'981 m <sup>3</sup>	637'191'083 m <sup>3</sup>	+1,61%
1930	675'921'078 m <sup>3</sup>	615'088'181 m <sup>3</sup>	-3,47%
1933	659'420'032 m <sup>3</sup>	600'072'229 m <sup>3</sup>	-2,44%
1954	598'531'240 m <sup>3</sup>	544'663'428 m <sup>3</sup>	-11,81%
1968	546'119'097 m <sup>3</sup>	496'968'378 m <sup>3</sup>	-8,76%
1975	537'462'786 m <sup>3</sup>	489'091'135 m <sup>3</sup>	-1,59%
1988	538'632'622 m <sup>3</sup>	490'155'686 m <sup>3</sup>	+0,22%
1991	533'781'613 m <sup>3</sup>	485'741'268 m <sup>3</sup>	-0,90%
1998	525'346'674 m <sup>3</sup>	478'065'473 m <sup>3</sup>	-1,58%
2000	506'282'962 m <sup>3</sup>	460'717'495 m <sup>3</sup>	-3,63%
2004	487'535'592 m <sup>3</sup>	443'657'389 m <sup>3</sup>	-3,70%

The input parameters for the Haerberli model were therefore not significantly different: this is reflected in the measured volumetric difference, which was very small. The described morphologic change is easily highlighted by DEM analysis, which was found to be a good tool for integrating other kinds of data. The integration of all the above methodologies allows a better understanding of glacial dynamics, providing necessary data for monitoring glaciers.

#### EQUILIBRIUM LINE ALTITUDE

Hypsographic curves of the areal extent-elevation of Rutor Glacier were generated. Based on these curves, the Equilibrium Line Altitude (ELA) was calculated using a 2:1 ratio between the accumulation and ablation basins.

The ELA was 2775 m during the maximum extent of the LIA and 2850 m in the period between 1975 and 1991.

The ELA rose in one century, with an increase of 75 m in half a century. Fig. 3 shows the hypsographic curves for the LIA, 1975 and 1991. These data agree with the trend of Val d'Aosta glaciers studied by Vanuzzo (2001): the rise in the mean ELA from the LIA maximum to 1975 is 33 metres for Val d'Aosta glaciers facing North, and 117 metres for those facing North-West.

## CONCLUSIONS

Like the majority of Italian alpine glaciers, Rutor Glacier retreated considerably after the Little Ice Age.

The results of this study indicate that the glacier has been retreating continuously over the last two centuries, with two interruptions determined by cold periods. The terminus advanced during the first interruption, between 1916 and 1926; glacier retreat ceased during the second interruption, between 1970 and 1990, with a slight advance occurring mainly in the Eighties. Some undated, small moraines near the present Rutor Glacier terminus probably relate to this period (about 1985 according to CGI data). This trend agrees well with literature climate series and other glacier studies.

The ELA 2:1, an important parameter for glacier retreat, increased by 75 m in the analysed time interval, in keeping with the general trend of glaciers in the western Alps facing North-North West.

From the Nineties to the present day Rutor Glacier has retreated considerably, probably in relation to global climate change. Linear retreat and loss of surface area seems to be gradually increasing in these decades. Studies on its volumetric evolution are in progress and will allow a better understanding of this retreat.

The role of GIS technology in this type of study is to support traditional methods of morphologic analysis by facilitating data processing and management. In the coming years other techniques may support this study: digital photogrammetry and remote sensing can be used to create DEMs to update the database, while radar technology may be used to study bedrock morphology and subsequently estimate the total glacier volume.

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