Morphodynamics of glacier lakes resulting from continued glacier shrinkage: Past evidence and future scenarios in the Western Italian Alps

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Abstract

Shrinkage and disappearance of glacier masses are producing substantial modifications in high mountain environments. At the end of the Little Ice Age (LIA, ca. 1850 AD) glaciers started to retreat and glacially sculpted landforms became exposed offering suitable conditions for lake formation behind frontal moraines and glacier-bed overdeepenings, and for their successive evolution (appearing/disappearing, expansion/shrinkage), as shown by Emmer et al. (2015) and Salerno et al. (2014).

Glacier lakes are of considerable significance, representing both opportunities and risks in densely populated and developed regions such as the European Alps (Haeberli et al., 2016a). Glacier lake inventories, containing information about the spatial distribution of glacier lakes and their geomorphological characteristics, represent a fundamental requirement for providing both, wide spatial and temporal overview of the phenomenon.

The overall aim of the present PhD thesis is to contribute to enhance the knowledge on the evolution of the alpine glacial landscape, from the past (end of the LIA) to the future, by focusing on glacier lakes.

The main objectives are:

1) to understand where and when glacier lakes formed and how they developed;

2) to assess where future lakes could appear, considering future glacier retreat scenarios.

A multiscale (regional and local) and multitemporal (past and future) approach is adopted, integrating different information technologies (GIS; remote sensing including aerial photogrammetry and LIDAR; database; modelling and georadar) and focusing on the glacierized Western Italian Alps (Piemonte and Aosta Valley).

The first goal is reached through the production and successive analysis, based on interpretation of historical maps and orthophotos, of six glacier-lake inventories related to the 1930s, 1970s, 1980s, 1990s, 2006-07, 2012. This information was combined with information from the glaciological surveys (1927-2014) documented in an *ad hoc* created database. Among the main findings are:

- about 250 lakes have been recognized within LIA boundaries;
- the majority of lakes are dammed by the bedrock;
- there are interesting examples of moraine-dammed lakes in the Gran Paradiso Chain of 1920s and 1970s;
- supraglacial lakes were found on the surface of Miage and Belvedere debris-covered glaciers;

- the disappearance of lakes was mainly due to infilling processes;
- lakes progressively increased in number and area until 2006-07.

Decrease of both the total number and total area of glacier lakes in 2012 with respect to the previous inventory (2006-07) is unexpected, in particular because glaciers continued to retreat. The reason of this difference is probably do to the data source: the 2012 orthophotos were taken in the first half of July 2012, when the snow cover was considerably extended on the investigated areas; this prevented to understand whether some lakes (32) survived or disappeared.

Concerning the assessment of possible future lakes, the Glacier Bed Topography model version 2 (Frey at al., 2014; Linsbauer et al., 2016) was tested and validated, for the first time, on the glaciers of the Aosta Valley Region. About 46 possible overdeepenings (>10000 m^2) could appear in the future and could be filled with water. Their total area is estimated at about 3 km^2 and their volume at 0.06 km^3, corresponding to less than 1% of the total glacier volume. Possible future lakes will be located mainly in the Monte Rosa massif and in the Gran Paradiso chain that are the same areas where the majority of the existing lakes are located. A validation of the obtained results is achieved by applying well-known methodologies: GPR surveys (at Indren, Gran Etret and Rutor glaciers) and morphological criteria (Frey et al., 2010). In addition, a new way for the validation is proposed: the backward approach. It is based on the use, as input data for the modeling, of historical datasets (DEM and glacier outlines) so that the model results (overdeepenings) can be compared with the reality (existing lakes or corresponding flood plains) for these areas left by the glacier in the years between the input data survey and now. It is found that the location and areal size of the modeled overdeepeenings is quite robust but that a higher level of uncertainty remains considering their morphometric parameters (depth and consequently volume).

The effort of this PhD thesis of creating a wide temporal and spatial overview of glacier lakes is intended as a contribution for enhanced understanding of where and how present glaciated environments of the Alps will change in the future from a glaciological and geomorphological point of view. Moreover, it will favour a more resilient behavior of alpine communities, by offering useful data as a knowledge base for elaborating comprehensive management strategies concerning originally glacierized but in future deglaciated landscapes, both in terms of opportunities (water supply, hydropower production, tourism) and hazards (glacier lake outburst floods).

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Abbreviations

ARPA	Regional Agency for the Protection of the Environment
CGI	Italian Glaciological Committee
DEM	Digital Elevation Model
GIS	Geographic Information System
GlabTop2	Glacier Bed Topography 2
GLOF	Glacier Lake Outburst Flood
GPR	Ground Penetrating Radar
GSD	Ground Sample Distance
IGMI	Italian Military Geographical Institute
ISMSA - SOIUSA	International Standardized Mountain Subdivision of the Alps - Suddivisione Orografica Internazionale Unificata del Sistema Alpino
LIA	Little Ice Age
NELAK	New lakes in deglaciating high-mountain areas
VdA	Valle d'Aosta
WIA	Western Italian Alps
WMS	Web Map Service

1 INTRODUCTION

1.1 MOTIVATION

Starting from the end of the Little Ice Age (LIA, ca. 1850 AD) a general and progressive shrinkage of the glaciers began in the European Alps, only interrupted by two temporary glacial advances occurred during the years 20s and 70s of the previous century (Zemp et al., 2008). As a result, European glaciers lost about 1/3rd of their area between 1850 and 1980 (EEA, 2004) and an additional 30% since the mid-1970s (Paul et al., 2011). Considering volume, glaciers lost half of it between 1850 and 1975, about 25% of the remaining between 1975 and 2000 and an additional 10 to 15% in the first 5 years of the XXI century (Paul et al., 2004; Zemp et al., 2006; Haeberli et al., 2007). Since the 1980s, glacial retreat has been continuous and scientific literature indicates that by the end of the 20th century it dramatically accelerated worldwide (Paul et al., 2004; 2011; Zemp et al., 2008; 2015). It is expected that the rapid retreat of glaciers due to the ongoing atmospheric warming will continue in the future and include the possibility of glacier disappearance in the next few decades in many mountain regions (Zemp et al., 2006; Huss & Farinotti, 2012; IPCC, 2013).

The disappearance of glacier masses produced substantial modifications in high mountain environments: new alpine geomorphological landscapes are forming, creating new opportunities and risks (Haeberli et al., 2016a). One of the most evident geomorphological effect is the formation of glacier lakes in recently deglaciated areas (Linsbauer et al., 2009). Most of these new lakes are located within “basins” due to bedrock depressions or moraine dams (Frey et al., 2010a; Emmer et al., 2015). As a consequence, progressive retreat of glaciers is followed by increasing number of new glacier lakes (Paul et al. 2007; Mergili et al., 2013; Emmer at al., 2014; Salerno et al., 2014; Carrivick & Tweed, 2013) and by significant morphological changes (appearing/disappearing, expansion/shrinkage) in the existing ones that reflects climatic fluctuations and environmental change (Salerno et al., 2014, 2016; Zhang et al., 2016).

Glacier lakes, especially in densely populated mountain regions such as the European Alps, are of considerable significance, other than for their scientific interest (geomorphological and glaciological significance), due to several reasons (NELAK, 2013; Salerno et al., 2014; Čiamporová-Zat’ovičová & Čiampor, 2017): 1) their potential economic value (e.g. for hydropower production, tourism activities and as water reservoir); 2) their environmental relevance for high mountain ecosystems and biodiversity; 3) the associated potential hazards (e.g. lake outburst and consequent flood).

For all these reasons, understanding conditions of formation and evolution of glacier lakes and their distribution has become a need, as demonstrated by the number of previous studies related to these issues.

A fundamental requirement for investigating these dynamic systems are datasets containing information about the spatial distribution of glacier lakes and their morphological characteristics, i.e. glacier lake inventories. In fact, regional inventories of glacier lakes are considered essential sources for both wide spatial and temporal overview of the phenomenon and for providing basic data for further applied purposes (Carrivick & Tweed, 2013).

Right now, manual digitalization on orthophotos or semi-automatic classification of optical remotely sensed images are well established to detect and map glacier lakes starting from the middle of the XX century. Approaches for assessing ice thickness and consequently glacier bed topography underneath present glaciers have recently been presented and assessed (Farinotti et al., 2017) permitting to identify the location of potential future lakes.

At the time when this thesis started, no lake inventories were found in the literature going back in time before the middle of the XX century. Moreover, comprehensive studies that take into account both past evidence of glacier lake formation and evolution and potential future scenarios of glacier lakes appearance were not many (Frey, 2011). Finally, very little was known about glacier lakes in the Western Italian Alps constituting a gap in the knowledge of the phenomenon in the European Alps.

Research related to the issues discussed above (i.e.: formation and evolution of glacier lakes in the past and as a consequence of future developments) bears different challenges: try to go back in the past before the middle of the XX century for reconstructing condition of formations and evolutionary steps of glacier lakes and having a wider temporal overview of the phenomenon dynamics; integrate data from the past and the future in a comprehensive wide spatial and temporal study of glacier lakes focusing on the Western Italian Alps as study region.

1.2 OBJECTIVES AND RESEARCH QUESTIONS

Glacier lake inventories are the core topic of this thesis. All objectives and research questions have a relation to glacier lake inventories: they include methodological issues, data compilation in a specific region, and further applications of such datasets, for investigating conditions of formation and evolution of glacier lakes. Research questions, presented in the following, will be progressively addressed in the present PhD thesis and answered in the last chapter.

Formation and evolution of glacier lakes in the Alps since the end of the Little Ice Age

The first goal of the thesis is to obtain a wide temporal (from the end of the LIA until now) and spatial (Western Italian Alps) overview of glacier lakes in order to better understand their condition of formation and evolution. A literature review about the topic (c.f. Section 2.2) shows that several studies exist, focusing on several mountain regions of the world (Gardelle et al., 2011; Salerno et al., 2014; Emmer et al., 2015, 2016) but none of these go back since the end of the LIA. Moreover, the Western Italian Alps have never been taken into account for multitemporal studies on glacier lakes. Therefore, the main issue is to investigate data sources and procedures for collecting information about the past and to integrate it with well-established methods for the compilation of glacier lake inventories (Huggel et al. 2002, Frey et al. 2010b). This leads to the first research question:

How is it possible to reconstruct the formation and evolution of glacier lakes since the end of the LIA?

Based on the findings of this investigation, several glacier lake inventories related to various time intervals for the study region are produced, supported by a database storing of additional information. The analysis of the datasets from each inventory and a multitemporal mutual intercomparison of the data allows to answer the second question:

Where and when did glacier lakes appear since the end of the LIA and how did they develop through time?

Potential sites for future glacier lakes

Since new lakes are expected to form because of glacier retreat, opportunities and hazards will arise due to the formation and evolution processes of future glacier lakes. The detection and assessment of sites suitable for potential lakes is thus of significant importance. Several studies presented approaches for modeling the location and morphometric characteristics of glacier-bed overdeepenings as sites of possible future lake formation and were applied in different mountain regions of the word (Linsbauer et al., 2012, 2016; Colonia et al., 2017). The assessment of the potential location of future lakes is possible through ice thickness modeling and the consequent production of a DEM without glaciers (Linsbauer et al., 2009). Sites of possible lakes correspond to modeled overdeepened areas in the bedrock underneath existing glaciers.

The second goal of the present research is to assess the location of potential future lakes for a test region, the Aosta Valley. This region has been selected for its wide glacier extension, thus being significant for providing information about future lakes (the first attempt in the Italian Alps) and adding information on this topic from a new studied region of the European Alps. The related research question is:

Where are future glacier lakes likely to appear?

Generally, results of these approaches are validated through the comparison with measurements taken by in-situ geophysical investigations (e.g., radio echo sounding) which are logistically and economically demanding and, sometimes, of difficult availability. The results and the suitability of the model is evaluated using new ways in addition to those used in existing studies:

How can the quality and reliability of modeled glacier-bed topographies be evaluated?

1.3 ORGANIZATION OF THE THESIS

The thesis is divided into 8 chapters.

In the introduction, the motivation of the research is explained followed by the objectives and related research questions. The current state of research is reviewed in Chapter 2. In Chapter 3 the methodological approach designed for the research project is defined. A general overview of the study area is given in Chapter 4. Chapters 5 (past evidence) and 6 (future scenarios) form the core of the thesis: specific objectives, data sets, methods, results are described. In Chapter 7 a general discussion of the main findings and of the adopted methods is given. Chapter 8 provides a summary of the main findings, conclusions and an outlook on the perspectives for future research. References close the dissertation.

2. THEMATIC AND SCIENTIFIC BACKGROUND

2.1 GLACIER LAKES: CLASSIFICATION AND IMPORTANCE IN THE EUROPEAN ALPS

Glacier lakes are masses of water impounded by ice, glacier deposits or glacial landforms (Ashley, 1995). Several classifications exist based on different criteria, the most widely used are based on: the position of the lake with respect to the glacier (Ageta et al., 2000; Gardelle et al., 2011; Zhang et al., 2015), the type of the dam (Galluccio, 1998; Carrivick & Tweed, 2013) and a combination of both of them (Ashley, 1995; Salerno et al., 2016; Emmer et al., 2015). Classifications depend also on the studied region and the characteristics of its lakes. For example, Salerno et al. (2016) proposed a specific classification for lakes of high mountain Asia. Galluccio (1998) identified the most representative type of lakes in Lombardy Region (Central Italian Alps) after having observed them for 20 years.

Here a simple classification of alpine glacier lakes is proposed, based on the above-mentioned existing classifications. Some visual examples are also presented for better explaining the different types of lakes within the classification (fig. 2.1).

According to their position with respect to the glacier, lakes are categorized in: 1) *supraglacial* lakes and 2) *proglacial* lakes. *Supraglacial* lakes (1) are those located on the surface of debris-free (fig 2.1a) or debris-covered glaciers (fig. 2.1b). *Proglacial* lakes (2) are located in recently deglaciated areas (after the end of the LIA, in the present study) and can be impounded by moraine/debris (fig. 2.1c) or by a bedrock threshold (in glacial overdeepened morphologies; fig 2.1d). If the proglacial lake is in contact with the glacier mass, it can be also named as ice-marginal lake. Subglacial (under glacier mass) and englacial (inside the glacier mass) lakes will not be included in the present study because they cannot be detected and mapped by remote sensing techniques (not visible at the surface).

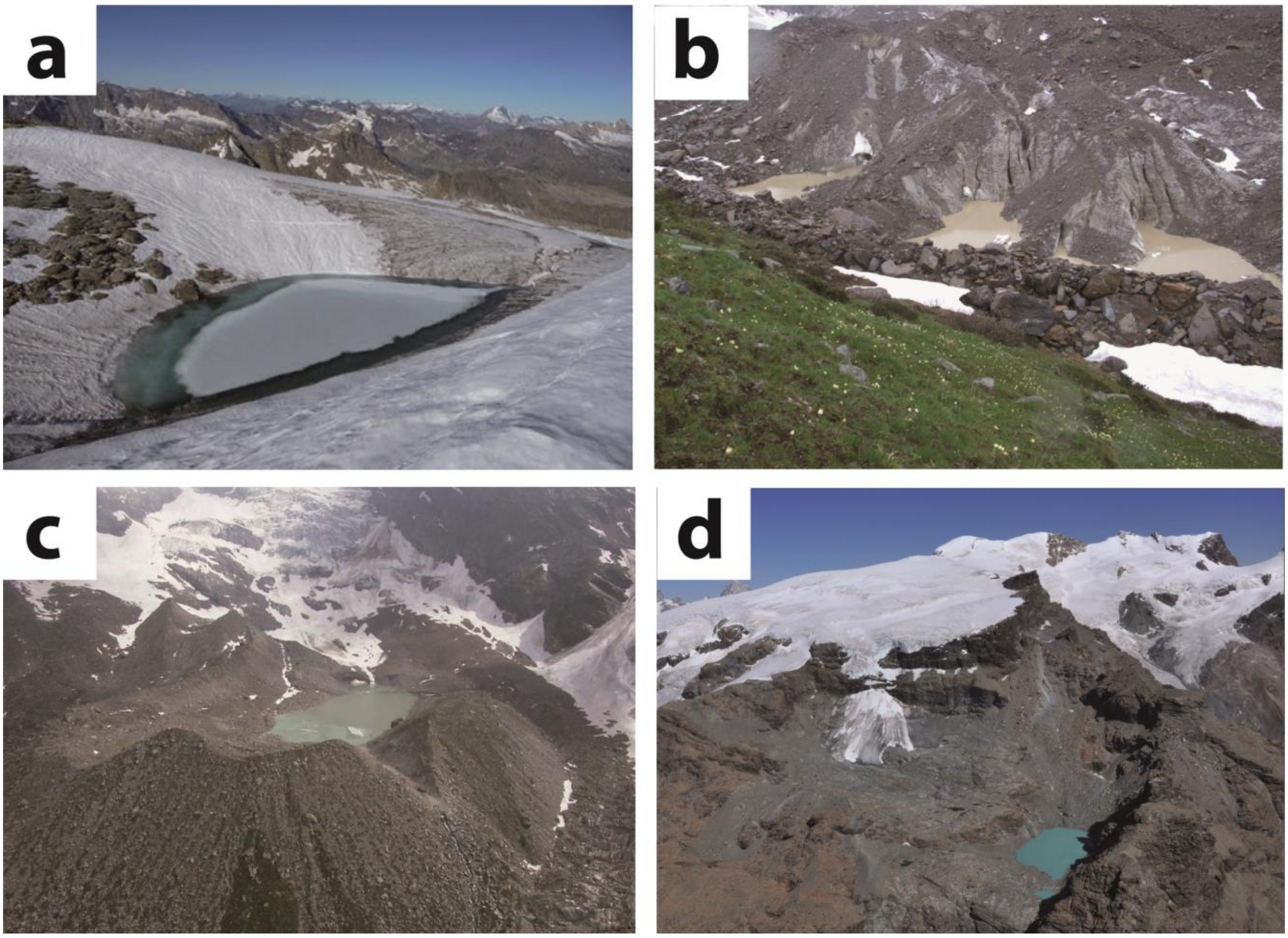


Figure 2.1 - Main types of glacier lakes with respect to the proposed classification: a) supraglacial lake on debris-free glacier (Moncorvè Glacier, Gran Paradiso chain; Panoramio website, undated); b) supraglacial lakes on debris-covered glacier (Belvedere Glacier, Monte Rosa massif; ph. Mortara, 2011); c) proglacial lake dammed by a frontal moraine, in the picture the artificial drainage cut for regulating the lakes level is visible on the right (Locce North Glacier, Monte Rosa massif; ph. Dipartimento Protezione Civile Nazionale, 2002); d) proglacial lake in bedrock overdeepening (Tzere Glacier, Monte Rosa massif; ph. Fondazione Montagna Sicura, 2012).

The importance of glacier lakes in the European Alps is shown in different studies, in particular the NELAK project conducted in Switzerland (NELAK, 2013; Haeberli et al., 2016a) and the ongoing FUTURELAKES project in Austria (http://www.georesearch.ac.at/en/areas/research-areas/geo/project-futurelakes/). Haeberli et al. (2016a) show the importance of existing and new lakes in terms of possible resources and related hazards and risks. As possible resources, they mention water supply, hydropower and tourism. Among the hazards and risks, there are floods and debris flow from lake outbursts caused by impact waves from rock/ice avalanches into lakes or dam breach. The Austrian FUTURELAKES project, aiming at understanding and modelling the development of glacier lakes in the study region, underlined the environmental and socio-economic impacts of glacier lakes on high mountain systems including water resource management, sediment delivery, natural hazards, energy production and tourism.

2.2 GLACIER LAKE INVENTORIES AS FUNDAMENTAL DATASETS FOR MULTITEMPORAL STUDIES

Inventories of glacier lakes are considered essential sources for both first and general overview of the phenomenon and for providing basic data for further purposes (Carrivick &Tweed, 2013).

2.2.1 Glacier lake inventories worldwide

The importance of regional glacier lake inventories is demonstrated by the number of studies dealing with this topic worldwide. Studies on glacier lakes have been carried out in some of the most important high mountain regions of the world since the beginning of the XXI century.

The majority of the studies refers to areas located in Asia and specifically: across the Himalaya region (Gardelle et al., 2011; Worni et al., 2013; Zhang et al., 2015; Salerno et al., 2016), around Mount Everest (Wessels et al., 2002; Bolch et al., 2008; Tartari et al., 2008; Salerno et al., 2012), the Tibetan Plateau (Zhang et al., 2016), in the Tien Shan (Bolch et al., 2011) and in Bhutan (Komori, 2008). There are also examples of regional researches in South America, across the Andes (Loriaux & Casassa, 2012; Hanshaw & Bookhagen, 2014; Emmer et al., 2016). Some studies refer to Iceland (Schomacker, 2010), Alaska (Capps & Clague, 2014) and the Caucasus (Stokes et al., 2007). Concerning the European Alps, studies were conducted in Switzerland (Huggel et al., 2002; Paul et al., 2007; Frey et al., 2010b), Western Austria (Emmer et al., 2015) and Italy (Galluccio et al., 1998; Salerno et al., 2014).

2.2.2 Creation of glacier lake inventories

Detecting and mapping glacier lakes is usually performed by remote sensing techniques. In the majority of the studies, inventories are produced by automatic classification of optical satellite images that is based on the spectral signature of water with a strong absorption in the NIR and SWIR wavelengths. The most widely used method is to calculate the normalized difference water index (NDWI) developed by Huggel et al. (2002). It allows identifying and mapping lakes on wide study areas in relatively short time. The main problem of mapping lakes via classification of optical satellite images is related to areas in shadow, quite frequent in mountain areas. Shadowed areas can be misclassified as lakes because of their high reflectance in the shortwave part of the VIS range. For identifying these areas, shadow mask is generated using DEM (not everywhere of high resolution) and calculating the sun elevation angle and azimuth at the time of the image acquisition. Misclassified areas are excluded but if a lake is in shadow, it cannot be identified and mapped. Other problems are related to frozen lakes or lakes covered by ice and snow. In the majority of the studies using this approach the classification through the NDWI is followed by visual inspection to browse and detect unclassified lakes. This approach is normally applied to Landsat images.

Wessels et al. (2002) used a similar approach on ASTER images, because of their higher spatial resolution and the four bands in the VNIR and MIR (Middle Infrared). They computed band ratios to distinguish water surfaces from non-water-surfaces and after, among water surfaces, solid (ice or snow) from liquid (free water) surface. This approach works well with ASTER images but is not enough robust for classifying images whose channels differ from ASTER sensor.

Strozzi et al. (2012) used very high resolution SAR data for detecting lakes and complementing information retrieved by high and very high-resolution optical images. The approach is based on the good visibility of water surfaces in SAR images. In fact, these surfaces have a low backscattering intensity at all microwave wavelengths (Strozzi et al., 2000). Lakes are mapped manually by the interpretation of SAR images. Authors underlined the advantages of SAR sensors with respect to the optical one because they are cloud-free data not weather dependent. Moreover, they provide a good timeliness of the data. On the other hand, during the data interpretation, some mistakes could be done because of the very low backscattering intensity of wet snow and wet sand areas that can be confused with water. Problems derive also from the presence of icebergs and ice debris floating on the lakes that can be confused with land.

There are also examples in the literature of inventories produced by manual detection and digitalization of lake outlines on aerial photos. Salerno et al. (2012; 2014) use and demonstrate the importance of aerial photos as the most suitable data sources for detecting and mapping lakes with small surface areas and for minimizing the uncertainty in multitemporal studies (change detection). In fact, the uncertainty of lake surface measurement is a function of the sensor resolution and its perimeter (fig. 2.2). For mapping relatively small lakes with a low error, high-resolution sensors are necessary but these kind of sensors are available only for the most recent years and not for going back in time as needed for multitemporal studies.

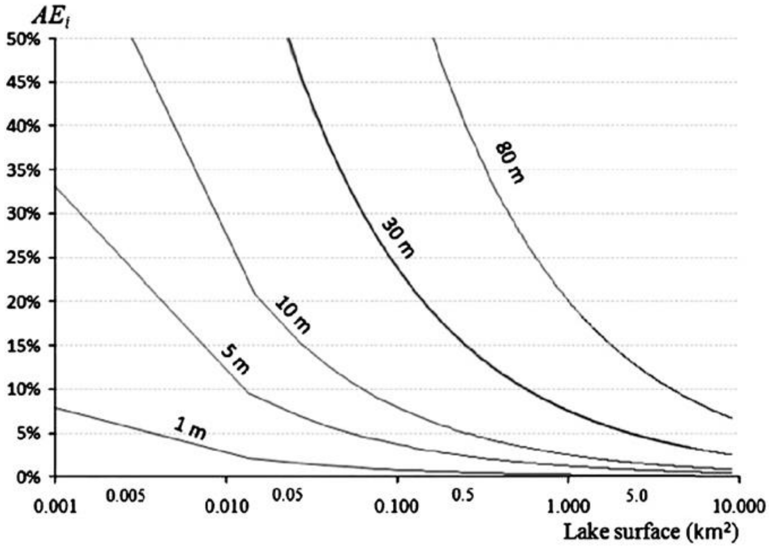


Figure 2.2. Graph representing the uncertainity of lake surface measurements (y) with respect to the lake perimeter (x) and sensor resolution (lines). (From Salerno et al., 2012).

Finally, there are few and very recent cases of topographic maps used as data sources for lake detection and mapping (Capps & Clague, 2014; Salerno et al., 2016). The use of historical maps enables to enlarge the time period on which analyzing lakes formation and evolution: Capps & Clague (2014) were able to analyse glacier-dammed lakes evolution at Brady Glacier starting from the beginning of the XX century thanks to the first topographic map with ice contours made during the Canada - U.S. International Boundary Survey in 1907. Salerno et al. (2016) performed a long-term analysis of surface area changes in Himalayan ponds integrating satellite imagery with the topographic map of the Indian Survey of the year 1963.

2.2.3 Application of glacier lake inventories

The importance of producing lake inventories is demonstrated by a number of studies. By the analysis of the existing literature (tab. 2.1), three main types of applications can be addressed.

1) Overview of the temporal and spatial distribution, conditions of formation and evolution of glacier lakes. There are several studies related to this category, some of them are reported below as examples. As a whole, they demonstrate the importance of producing wide spatial and temporal inventories of glacier lakes for understanding their evolution and for relating it with glacier change through time. Galluccio (1998) provided a spatial overview of glacier lakes of Lombardy Region (Central Alps, Italy) focusing on the period of formation (before or after the short glacier advance occurred in 1975-1985), geographical location, elevation, type, associated risk. Salerno et al. (2012) provided a complete mapping of glacier lakes in the Mount Everest region for the year 2008 and analysed condition of formation of supraglacial, proglacial and unconnected glacial lakes. Finally, Hanshaw & Bookhagen (2014) produced lake-area outlines for the Cordillera Vilcanota region from 1975 to 2012. Lakes evolution in the considered time period has been analysed in relation with glacial areas changes. Zhang et al. (2015) conducted the first glacier lake inventories for the Third Pole for 1990, 2000 and 2010. They analysed lake spatial distributions and areas and temporal changes relating it to their location with respect to the glaciers and to their elevation.

2) Understanding lakes changes in response to climate change.

Creation of glacier lake inventories and their multitemporal analysis are essential steps, not only towards a better understanding on glacier evolution and dynamics, but also for an improved knowledge on climate changes. Gardelle et al. (2011) presented a first regional assessment of glacier lake distribution and evolution in the Hindu Kush Himalaya between 1990 and 2009. They find that there are differences in the number, area and type of lakes between the eastern and western part of the study area, which remains valid also for lake expansion. Lake evolution gives an insight not only concerning climate variations (temperature and precipitation) but also, indirectly, of the changes in the Hindu Kush Himalaya cryosphere (glacier length mass changes). Salerno et al. (2014) analysed more than 100 water ponds in the Ortles-Cevedale mountain group (Southern Alps, Italy) between 1954 and 2007. The changes in number, area and elevation of the lake population have been related both to the glacial shrinkage and retreat and to the climate trend of the study area (temperature and precipitation). In particular, the study demonstrates how the surface area changes of lakes is a signal of the impact of climate change on alpine environments. Salerno et al. (2016) studied unconnected glacial ponds located on the south side of Mt Everest over the last 50 years (1963-2013). Because of the high sensitivity of these ponds to climate change, the authors demonstrate that changes in pond areas could be tracked to detect the behavior of precipitation and glacier melt in regions where few climatic data and time series exist. Zhang et al. (2016) detected and studied glacier lakes for Asia’s two largest and adjacent plateaus (Tibetan and Mongolian plateaus), quantified drastically different changes and their evolutions over the last four decades. They found that the two adjacent plateaus have been changing in opposite directions and that the change is driven by large-scale atmospheric circulation changes in response to climate warming.

3) Assessment of the susceptibility of glacier lakes to outburst floods.

The following examples demonstrate the importance of creating glacier lake inventories in order to identify cases that need more detailed and comprehensive studies because of the potential associated risk (Allen et al., 2009) and successive planning of adequate coping strategies. Worni et al. (2013) presented a first area-wide inventory of glacier lakes in the Indian Himalaya. Lakes were classified by a qualitative approach based on the dam type and geometry, freeboard and potential for lake impacts. The inventory allowed assigning a general outburst probability for the single lake (critical lake, potentially critical lake, uncritical lake) and identifying the most critical lakes for further field and remote sensing investigations and model application in order to assess their hazard potential. A combination of specific parameters is used in order to model potential dam break (e.g.: fluid density, resistance factor, grains diameters, porosity, slope failure angle). Emmer at al. (2015) identified and quantitatively and qualitatively classified high-mountain lakes in Western Austria. After a change detection analysis, a Glacier Lake Outburst Flood (GLOF) susceptibility estimation of some selected cases has been performed (potential triggers, mechanisms of GLOFs, overtopping duration, peak discharge and impacted areas have been evaluated).

Emmer et al. (2016) produced an inventory of glacier lakes for the Cordillera Blanca of Peru. Detected lakes have been classified and described by qualitative (lake type according to the dam material, lake outflow, lake/glacier relation, catchement, lake situated upstream, remedial works, outburst flood) and quantitative (latitude, longitude, elevation, lake size) approaches. A multi-temporal analysis from 1948 to 2013 allowed to understand from what type of lakes GLOF originated in the past, moreover the susceptibility to outburst flood for large lakes was assessed using different procedures for different types of lake.

The research presented in this thesis could be attributed to the first category of studies.

References	**Region**	**Data**	**Method**	**Application**
Galluccio, 1998	Lombardy Region (Italy)	Observation and morphological data	Field surveies since 1998	Overview
Wessels et al., 2002	Mount Everest	ASTER	Automatic classification and manual correction	Overview
Paul et al., 2007	Switzerland	Landsat, ASTER	Flicker-image analysis Animated image sequences)	Overview
Stokes et al., 2007	Caucasus Mountain	Landsat	Manual digitizing	Overview
Komori et al., 2008	Bhutan Himalayas	Corona, Landsat, SPOT, topographic maps	Manual	Overview
Tartari et al., 2008	Sagarmatha National Park (Nepal)	Maps	Manual	Overview
Schomacker et al., 2010	Vatnajökull ice cap	Landsat	Manual	Overview
Gardelle et al., 2011	Hindu Kush Himalaya	Landsat	NDWI and visual inspection	Overview
Loriaux & Casassa, 2012	Northern Patagonia Ice Field	Map, Landsat	Manual delineation	Overview
Salerno et al., 2012	Mount Everest region	ALOS optical images	Manual	Overview
Strozzi et al., 2012	Switzerland, Tajikistan, Nepal	SAR data	Manual	Overview
Capps & Clague, 2014	Alaska	Maps, airphotos, optical satellite images (Landsat)	Manual	Overview
Hanshaw & Bookhagen, 2014	Northern central Andes	Corona, Landsat, ASTER	Band ratio and manual editing	Overview
Salerno et al., 2014	Ortles-Cevedale (Italy)	Aerial orthophotos	Manual	Climate
Zhang et al., 2015	Third Pole	Landsat	Manual	Climate
Salerno et al., 2016	Himalaya	Topographic maps, Corona, Landsat and ALOS images	Manual	Climate
Zhang et al., 2016	Tibetan Plateau	Landsat	NDWI and manual correction	Climate
Huggel et al., 2002	Switzerland	Landsat and SPOT	NDWI	Outburst
Bolch et al., 2008	Mount Everest region/Nepal	Corona, ASTER, Landsat	Band ratio, NDWI and manual editing	Outburst
Frey et al., 2010b	Switzerland	Landsat	Semi-automatic lake detection (NDWI + manual)	Outburst
Bolch et al., 2011	Tien Shan	Corona, ASTER, Landsat	Band ratio, NDWI and manual editing	Outburst
Worni et al., 2013	Indian Himalayas	Landsat and Google Earth images	NDWI and visual postprocessing	Outburst
Emmer et al., 2015	Western Austria	Optical satellite images (Google Earth Digital Globe 2014)	Manaul detection and digitalization	Outburst
Emmer et al., 2016	Cordillera Blanca, Andes	Historical aerial photos and recent optical images	Manual	Outburst

Table 2.1 - List of the main scientific papers related to the applications of glacier lake inventories. They are grouped firstly with respect to the three type of applications identified by the present thesis (overview, climate, outburst) and secondly in chronological order.

2.3 GLACIER-BED OVERDEEPENINGS AND POTENTIAL FUTURE LAKES

The shrinkage of mountain glaciers caused by climate change is expected to continue in the future (Zemp et al., 2006; IPCC, 2013). Some typical landforms emerge during glacier retreat, such as overdeepenings, defined by Haeberli et al. (2016b) as “closed topographic depressions with adverse slopes in the flow direction”. These characteristic landforms of glacier beds and glacially sculpted landscapes, after being exposed, in some cases are filled with water rather than sediments (Frey et al., 2010a). Consequently, detecting overdeepenings in the glacier bed allows to identify sites for the potential future formation of glacier lakes.

2.3.1 Assessment of bedrock topography and sites for potential future lakes

In 2009, Linsbauer et al. presented a GIS-based modelling approach for reconstructing glacier beds. It is a robust approach that, from a minimum set of input data (DEM, glacier outlines and flowlines), allows to construct digital elevation models “without glaciers” for currently glaciated mountain regions. The approach is based on the assumption that the glacier surface is a smoothed projection of the bedrock underneath the glacier (Oerlemans, 2001; fig. 2.3). The most important parameter for calculating ice thickness is the slope of the glacier surface: the steeper the glacier the thinner the ice and vice versa. Linsbauer et al. (2009) underlined the good agreement between modeled glacier beds and field measurements (GPR profiles). Moreover, they highlighted the potential of the approach for regional applications in the Alps and the adjustability of the model to different glacier types and climatic settings.

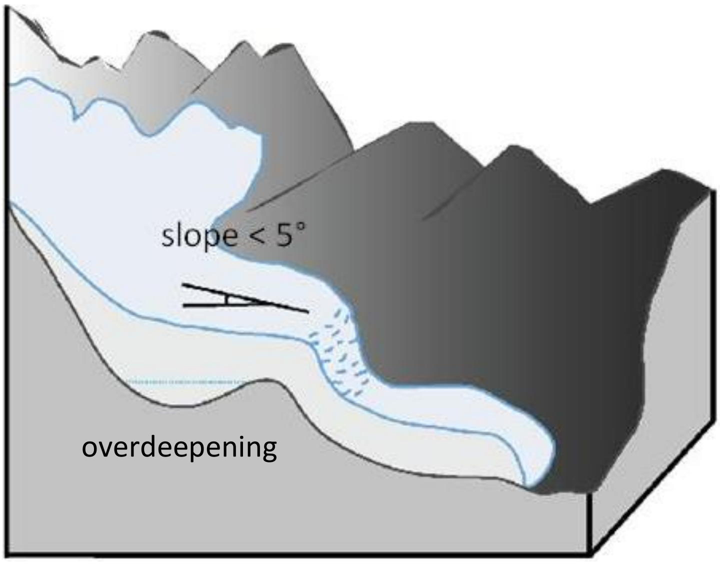


Figure 2.3 - Schematic illustration of the GlabTop approach principle (modified from Linsbauer et al., 2009).

Paul & Linsbauer (2012) explained the equation on which the approach is based. The ice thickness (d) is dependent from the slope (α) and the basal shear stress (τ) in the following way:

$$d = \tau / (f \rho g \sin\alpha)$$

where f is the shape factor (related to the friction of a real glacier with the valley walls), ρ the ice density (900 kg m^{-3}), g the acceleration due to gravity (9.81 m s^{-2}). The shape factor refers to the ratio between the cross-sectional area of the glacier and its perimeter. Generally, it is set as constant (0.8) which is the value typical for valley glaciers (Paterson, 1994). τ is often set as a constant value of 1 bar as a good starting point but it can be parameterized with the vertical extent Δh by the equation $\tau=0.005+1.598\Delta h-0.435\Delta h^2$ (Haeberli & Hoelzle, 1995) .

As mentioned before, the required input data sets are three: a DEM, glacier outlines and a set of center lines of major glacier branches that has to be manually digitized. Ice thickness is calculated at several points along the branch lines and then interpolated for each glacier to a continuous grid. Paul & Linsbauer (2012) analysed and commented the accuracy of the results, concluding that the modeled ice thickness is not better than ±20-30%. Nevertheless, they confirmed the robustness of the approach in modeling the general shape of the glacier bed and its suitability for assessing the location of overdeepenings.

Linsbauer et al. (2012) named for the first time the mentioned approach Glacier Bed Topography (GlabTop) model. The subtraction of the modeled ice thickness from a surface DEM provides an approximation of the bedrock topography for entire mountain ranges. The authors applied the model to large glacier samples of the entire Swiss Alps, they first calculated the spatial distribution of ice thicknesses and then assessed sites of potential future lake formation based on the analysis of the modeled glacier-bed topography. Linsbauer et al. (2012) confirmed that the values obtained by GlabTop are within a general uncertainty of ±30% and that the locations of modeled overdeepenings are robust. The topography of the glacier bed cannot be modeled at a high spatial resolution (25 meters in the case of mentioned study) because, for example, the surface smoothing is necessary for taking into account effects from longitudinal stress coupling.

Frey et al. (2014) presented a new version of the model: GlabTop2. It avoids the high demanding work of manually drawing the branch lines. In fact, GlabTop2 calculates the ice thickness for randomly and automatically selected DEM cells within the glacier area (auburn cells in fig. 2.4). The required input data are a DEM and the glacier mask, based on its grid the model calculates ice thickness at random cells and then interpolates the values in order to obtain ice thickness for all glacier cells. The authors used the mentioned approach for estimating ice volume in the Himalayan-Karakoram region, the modeled ice thickness values are in good agreement with direct observations.

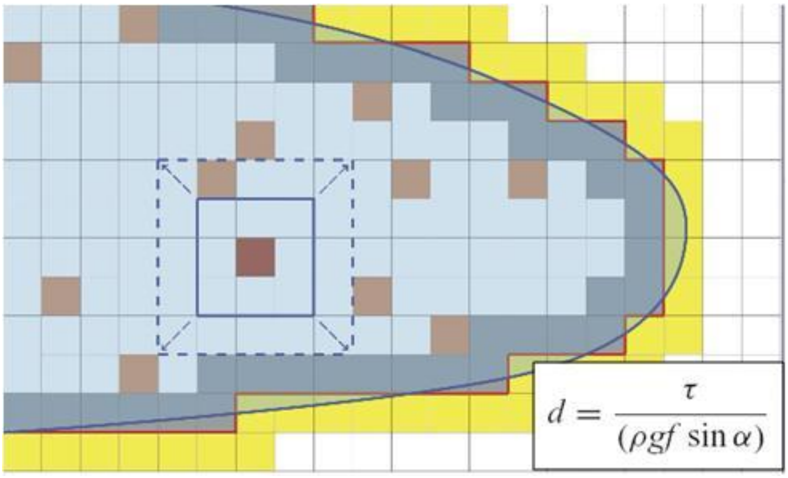


Figure 2.4 - Schematic illustration of GlabTop2 mode of operation (modified from Frey et al.,2014).

Frey et al. (2010a) presented a multi-level strategy for the detection of sites for potential glacier lake formation. The strategy allows to analyse, as a first step, wide glaciated region and to go successively into more detail in smaller regions. The objective is to identify critical sites where glacier lakes could form and develop in the future with associated hazard potential. The assessment of the location of potential overdeepenings starts with the analysis of the glacier surface topography through the DEM in order to identify surfaces below a slope threshold (5°). Moreover, three additional morphological criteria are defined: a distinct break in slope, a reduction in glacier width and a heavily crevassed glacier area below a crevasse-free area. Successively, models like GlabTop and GlabTop2 can be used to model the ice thickness distribution. Finally, in-situ geophysical survey or drilling can confirm and integrate the data (ice thickness and bed topography) extracted by the model.

Farinotti et al. (2009) presented a further method for estimating both the overall ice volume and the ice-thickness distribution of alpine glaciers from surface topography, based on mass turnover and principles of the ice-flow mechanics. The estimated accuracy is about 25%. This physically based method has been applied to small subsets of glaciers, but not at large scales because of the unavailability of the required data input. Huss & Farinotti (2012) presented a development of the method based on ice dynamical considerations (estimation of the surface mass balance distribution and calculation of the volumetric balance flux). They calculated ice thickness and volume for all glaciers worldwide using glacier outlines and DEM.

2.3.2 Methods for validating model results

Validation is a fundamental step for assessing model performances and quality. It is necessary to compare modeled results with real measurements (ground truth data). Different methods have to be mentioned for validating the models presented above: seismic, Ground Penetrating Radar (GPR), drilling. GPR has progressively replaced seismic soundings and, in combination with hot-water drilling, can be used for deriving bedrock information. The main problem of this type of measurements is their sparse availability. Moreover, their density on the glacier surface can be scarce and irregularly distributed because of steep areas affected by crevasses, snow avalanches or ice-/rockfall. Measurements are mainly carried out on the crevasse-free and flat areas where the ice of the glacier is thickest. A corresponding uncertainty remains with interpolation of such biased data to unmeasured sites.

Previous studies on glacier-bed topography assessment did direct comparison between modeled results and GPR measurements along selected cross section. The Ice Thickness Models Intercomparison eXperiment (ITMIX, Farinotti et al., 2017) is the first coordinated assessment quantifying individual model performances. The results of a set of 17 different models are compared over 21 considered test cases. Considering the GlabTop approach, it appears that its results are comparable in quality with more complex model approaches.

Very recently, Kapitsa et al. (2017) compared modeled and real overdeepenings. They analysed whether some of the modeled overdeepenings underneath glacier tongue have become real lakes and the main finding is that 67% of the lakes developed at the sites of the overdeepenings.

2.3.3 Potential future lakes worldwide

First applications of models for assessing glacier-bed topography and sites for potential future lakes have been carried out in the Swiss Alps. Linsbauer et al. (2009) showed preliminary results obtained by using the GlabTop approach in the Bernina region of Switzerland, one of the mentioned applications is the detection of overdeepenings in the glacier bed. Successively, Paul & Linsbauer (2012), in the same study region, went more in depth with the explanation of the model results and performances in assessing ice thickness and subglacial topography. Linsbauer et al. (2012) applied GlabTop to all Swiss Glaciers calculating their total volume using two sets of input data related to 1973 and 1999 (75±22 km^3 for 1973 and 65±20 km^3 for 1999). They obtained a DEM without glaciers and they detected overdeepenings in the modeled glacier beds (500-600 and 400-500 overdeepenings for the two years). The authors evaluated the model performance by comparison with GPR profiles at Rhone, Zinal and Corbassière glaciers. The multi-level strategy presented by Frey et al. (2010a) was applied at Aletsch and Trift glaciers and in the Bernina region, locations with potential future lake formation were delineated.

Successively, GlabTop2 model was used in the Himalaya-Karakoram region: by Frey et al. (2014) for calculating volumes for all glaciers (about 2955 km^3 ± 30%) and by Linsbauer et al. (2016) for modelling bed overdeepenings (16,000 overdeepenings, 2200 km^2 area, 120 km^3 volume) in the same study region. The authors discussed the results for specific test areas in four sub-regions (Karakoram, Western Himalaya, Central Himalaya and Eastern Himalaya). Comparison of GPR measurements with modeled ice thickness have been performed at Chhota Shigri Glacier.

Moreover, the multi-level strategy presented by Frey et al. (2010a) and the GlabTop2 approach were also used in combination with glacier surface slope classification in the Peruvian Andes (Northern, Central and Southern Andes) in order to compile an inventory of glacier-bed overdeepenings and potential new lakes (Colonia et al., 2017). The authors identified a total number of 201 overdeepenings with an estimated volume of about 260 million m^3.

Furthermore, Kapitsa et al. (2017) applied the GlabTop2 model in the Djungarskiy (Jetysu) Alatau region. 513 overdeepenings were modeled, with a combined area of 14.7 km^2.

3. METHODOLOGICAL APPROACH

The present chapter provides an explanation of the overall methodological approach applied in the present study. Specific data and methods used for the research will be described in the corresponding chapters.

In order to answer the research question defined in chapter 2 a multidimensional approach is adopted (fig. 3.1). Multidimensional approach includes both the temporal and the spatial dimension.

From a temporal point of view, the research is focused on the evidence related to the formation and evolution of glacier lakes in the past starting form the end of the LIA until the present days. An integration of different data sources is proposed in order to reconstruct the past evidence and have a wide temporal overview of the phenomenon. Moreover, the potential future appearance of new glacier lakes is investigated. The location of possible future lakes is assessed for the first time for selected Italian glaciers by an available model.

All the investigations are performed at the regional scale, and the same procedure is applied for the interpretation of the results and their discussion. This allows to provide a wide spatial overview of the phenomenon, in addition to a wide temporal one. The validation of the adopted methodology for reconstructing past evidence of glacier lakes is then achieved at the local scale, in order to demonstrate the importance of integrating different scales and data sources. Concerning the assessment of future scenarios, new solutions for the results validation are proposed and applied at the regional scale, in addition to application at the local scale of the well-known validation methodologies from the literature. In particular, the results from the first part of the research (past evidence) are used to validate the results obtained by the model.

The multidimensional approach is supported by an integration of different information technologies that includes the use of: Geographic Information Systems, Remote Sensing (aerial photogrammetry, LIDAR), database, modeling, georadar (fig. 3.1).

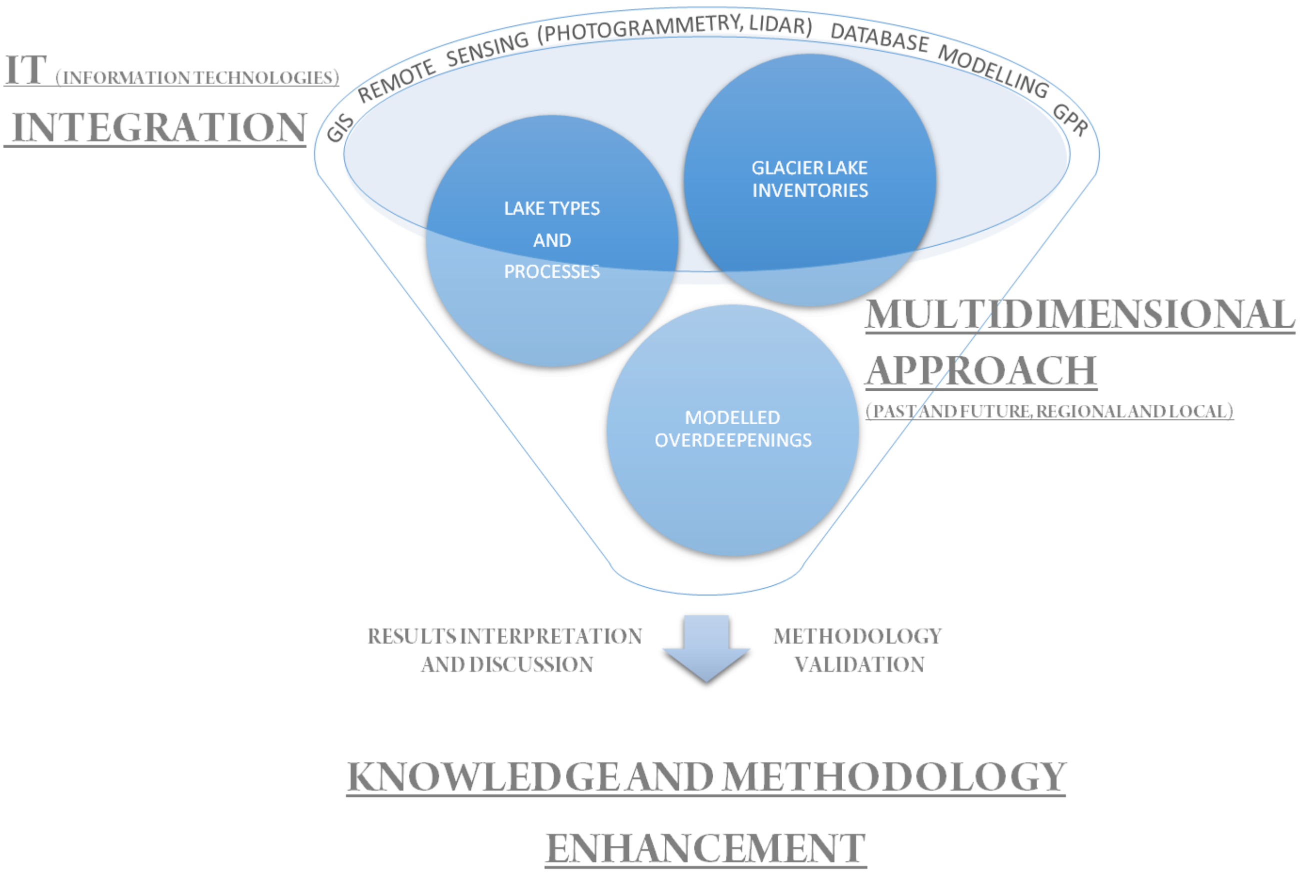


Figure 3.1 - Conceptual scheme of the proposed methodological approach.

4 STUDY AREA: GLACIERS AND GLACIER LAKES OF THE WESTERN ITALIAN ALPS

The study area covers the Italian side of the Western Alps within the mountain territories of Piemonte and Aosta Valley regions (fig. 4.1). It includes five Alpine sections (according to Marazzi, 2005): Maritime, Cottian, Graian, Pennine and Lepontine Alps. From South to North, the mountain arch of the Western Italian Alps encompasses approximately 250 km and only about 77 km from West to East.

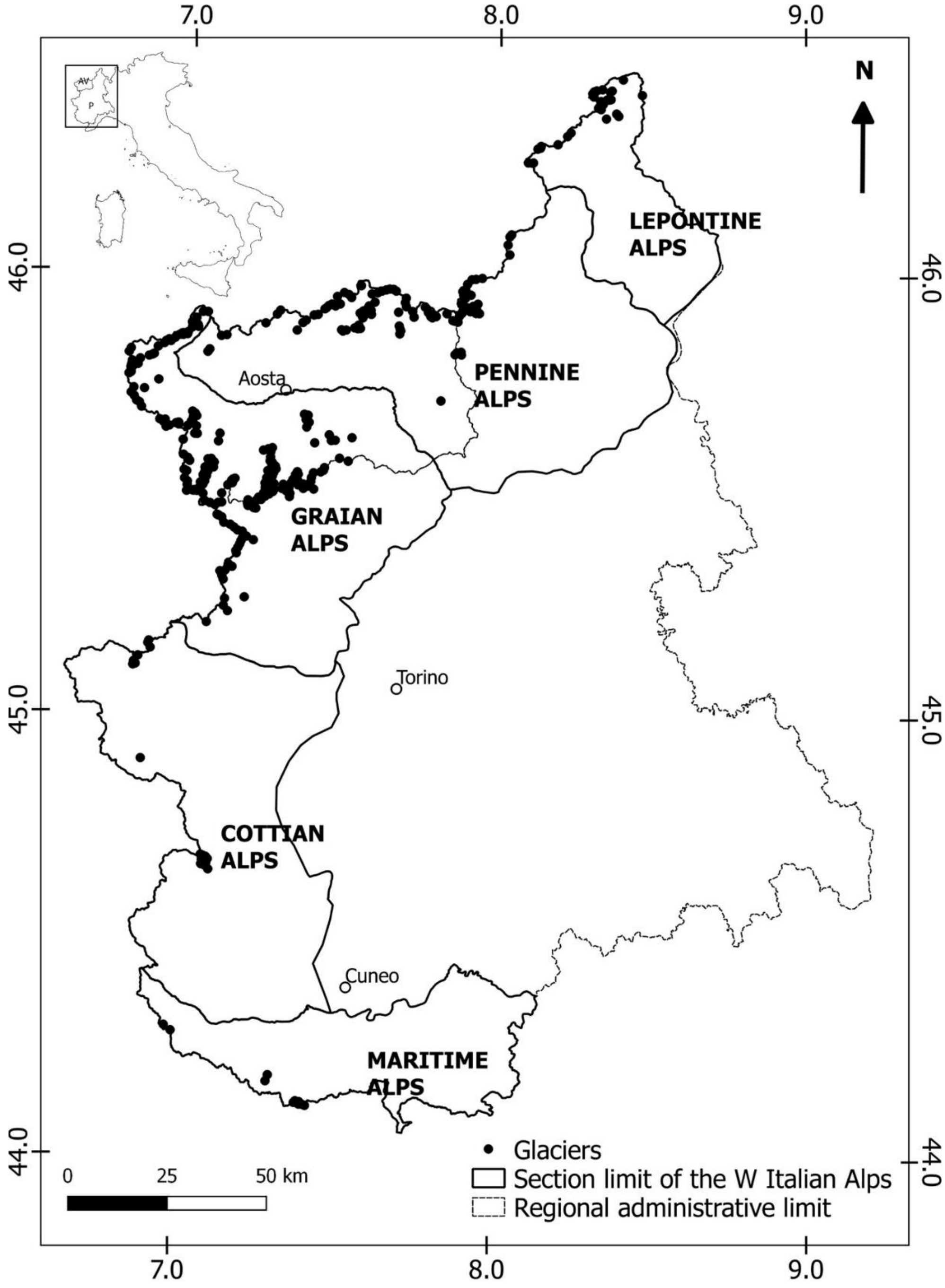


Figure 4.1 - Section of the Western Italian Alps according to the ISMSA-SOIUSA (Marazzi, 2005) and location of glaciers according to the Italian Glacier Inventory (CGI, 1961).

The internal (“Italian”) flank of the arc-shaped Western Alps, is shorter and steeper than the external one with a marked step from the Po Plain (200-300 m a.s.l.) to the mountains (1000-4800 m a.s.l.). The valleys are located radially around the Western Po Plain, their heads are mainly oriented towards NE, E and SE. Many of them were sculpted during the Pleistocene by large glaciers, which produced the typical U-shaped profile, morainic amphitheaters and lakes.

4.1 GLACIERS

The present study focuses on the areas within the glacier extent during the Little Ice Age (LIA). Thanks to the large amount of data, it is possible to reconstruct the extent and the evolution of most of glaciers in the Western Italian Alps from the end of the LIA until now (tab. 4.1). Maps of Federico Sacco clearly evidenced the extension of glaciers during the LIA (Sacco, 1918a; 1918b; 1918c; 1920; 1921; 1922; 1930), in a more recent time the GlaRiskAlp Project produced digital outlines of glaciers during the LIA for Western and South-Western Piemonte and Aosta Valley (about 390 km^2).

Within the study area, the first systematic inventory of Italian glaciers (CGI, 1961) developed by the Italian Glaciological Committee in cooperation with the National Research Council, reported glaciers covering a total area of about 240 km^2 at the end of the 1950s. Successive update of the inventory refers to 1989 based on the photogrammetric flight of 1988-89 (Ajassa et al., 1994; 1997). Some fractioning phenomena are reported together with a progressive shrinkage of glacial masses (total area 201,83 km^2).

Most recent works about the state of Italian glaciers are those of Salvatore et al. (2015) and Smiraglia et al. (2015). According to Smiraglia et al. (2015), present glaciers of the Western Italian Alps cover a cumulative area of 162.65 km^2 (44% with respect to the whole Italian glacial coverage). Concerning recent glacial withdrawal in Italy, the Piemonte Region shows the strongest decrease in glacial area between the 1960s and the present time (more than 40% of its previous coverage) and the Aosta Valley (the region with largest glacierized area of Italy) has given the largest contribution (24%) to the national glacier loss (30.5%). Salvatore et al. (2015) confirmed and highlighted the current trend of glacier extinction, areal reduction and fragmentation.

Lucchesi et al. (2014) calculated an area reduction of 77.8% between 1850 and 2006 for glaciers in the Western and South-Western Piedmont Alps.

Alpine section	LIA (GlaRiskAlp Project)		1958 (CGI, 1961)		1989 (Ajassa, 1994; 1197)		2006-07 (Salvatore, 2015)	
	N	Area km^2	N	Area km^2	N	Area km^2	N	Area km^2
Maritime	20	3.28	7	1.05	5	0.19	1	0.04
Cottian	21	6.15	14	3.39	12	0.87	5	0.22
Graian	228	269.31	180	136.65	198	123.83	198	101.73
Pennine	52	111.93	93	83.92	77	66.22	91	57.31
Lepontine	/	/	26	14.36	26	10.72	22	6.95
Total	321	390.68	320	239.37	318	201.83	317	166.25

Table 4.1 - General summary of the total number and total area of glaciers reported in the existing inventories for the Western Italian Alps.

At present, the main glacierized massifs are (from south to north) Gran Paradiso (4061 m), Monte Bianco (4808 m), Monte Rosa (P.ta Dufour, 4634 m) and Monte Leone (3553 m). As a matter of fact, glaciers of the Western Italian Alps are smaller than those in the rest of the Alps because of the limited moisture and the exposure to solar radiation (Williams and Ferrigno, 1993).

In addition to glacier shrinkage and fractioning, morphological changes happened: smoother surfaces and fewer crevasses are evidence of a low glacier activity. Moreover, changes in the type of glaciers are occurring too: from valley glaciers during the LIA to mainly mountain glaciers now. Finally, white and debris-free areas are becoming progressively debris-covered.

4.2 GLACIER LAKES

Specific cases of glacier lakes in the study area have been reported since the beginning of the 20th century, e.g.: Galambra in the Cottian Alps (Peretti, 1935), Locce in the Pennine Alps (Haeberli & Epifani, 1986; Tropeano et al., 1999), Rutor in the Graian Alps (Dutto & Mortara, 1992), Miage in the Graian Alps (Deline et al., 2004; Diolaiuti et al., 2006), Belvedere in the Pennine Alps (Mortara & Tamburini, 2009), Rocciamelone in the Graian Alps (Vincent et al., 2010).

Peretti in 1935 described the drainage of the ice-contact lake at the Galambra Glacier in the Graian Alps occurred in 1933. The water level lowered by 14 m and the areal dimension of the lake changed from 422 x 222 m to 62 x 28 m. Locce Lake, on the eastern side of the Monte Rosa massif above Macugnaga is a well-known and studied case of moraine-dammed lake (Haeberli & Epifani, 1986). In 1970, 1978 and 1979 several outburst floods took place. It was partially artificially drained in the 1980s because of the increase of the water stored in the basin (Tropeano et al., 1999).

Rutor Glacier present several lakes in its proglacial area, in particular the Santa Margherita lake is famous because of the several outburst floods occurred between 1430 AD and 1864 AD due to front fluctuations and described by Dutto & Mortara (1992).

The Miage Lake is of considerable significance both for its scientific and touristic interest. It has existed since the XVIII century. Deline et al. (2004) reported that several drainage events took place between 1930 and 1990. In particular authors analysed the event occurred in September 2004 when the lake measured 36000 m^2 of area and 30 m of depth. Diolaiuti et al. (2006) described rates, processes and morphology of freshwater calving at Miage Glacier into Miage lake.

The ephemeral lake formed on the surface of the debris-covered Belvedere Glacier (Pennine Alps, East side of the Monte Rosa, Macugnaga) is another notable case in the Western Italian Alps. It reached an area of 150000 m^2 and a maximum depth of 57 m, the consequent estimated volume being 3 million m^3. In order to prevent an imminent outburst, artificial drainage measures were installed in 2002. In the following years a natural drainage occurred and no evidence remained of the presence of the lake. The case was well described by Mortara & Tamburini (2009) and Harrison et al. (2014).

The lake dammed partially by the Rocciamelone Glacier and partially by a rock step became of international interest in 2001 because of its progressive enlargement, it reached 400.000-600.000 m^3 of volume and 25 m of depth. Thanks to artificial drainage the level was lowered in 2004 and 2005 and successively the natural drainage and the progressive shrinkage of the glacier emptied the basin. Field measurements and model simulation were carried out and described by Vincent et al. (2010).

The above-mentioned studies mainly focus on potentially hazardous conditions related to the presence of glacier lakes. Moreover, a comprehensive database containing information about events of Glacier Lake Outburst Floods (GLOF) in Europe has been realized, in the framework of the GlacioRisk project (http://www.nimbus.it/ghiacciai/glaciorisk.htm): it includes data from the Western Italian Alps. Finally, in the framework of the GlaRiskAlp project (http://www.glariskalp.eu/), an inventory of lakes formed since the 1980s has been produced for a sector of the Western Alps (Italy and France) that is only a part of the study area investigated in the present work.

As a matter of fact, our study of glacier lakes in the Western Italian Alps is intended to fill the gaps within results of previous studies and to offer a comprehensive analysis of glacier lakes over a long time period and a wide spatial scale (Western Italian Alps).

5 AN OVERVIEW OF GLACIER LAKES IN THE WESTERN ITALIAN ALPS FROM 1927 TO 2014

5.1 SPECIFIC OBJECTIVES

The main goal of the present chapter is to offer a wide temporal and spatial overview about the past evidence of glacier lakes in the Western Italian Alps.

The specific objectives to be reached are:

- to produce a set of inventories of glacier lakes within the study area, related to different time periods;
- to create an *ad hoc* database and to test an operational routine for collecting information (reports, photos, maps, etc.) about glacier lakes;
- to give a general overview of the morphometric, geomorphologic and geographic features of the lakes of each time period;
- to identify the main types of glacier lakes and processes
- to demonstrate, through selected cases, the importance of integrating different sources of data for the reconstruction of the formation condition, evolutionary stages and process dynamics of glacier lakes;
- to provide preliminary considerations on changes in the number of glacier lakes within the study area and the considered time period.

5.2 DATA SOURCES

5.2.1 Historical maps

The Italian Military Geographical Institute (Istituto Geografico Militare Italiano, IGMI) produced the first issue of the official topographic map of Italy at the end of the 19th century at a scale of 1:25,000. Successive updates have been published during the XX century. Those maps, with contour lines and relevant symbols also for high mountain sectors, can be used for geothematic mapping within glacial environment (Carton et al., 2003). Also previous historical cartographic documents such as the “Dufour”, “Sigfried” and “Stati Sardi” maps (beginning of XIX century; reviews on Aliprandi & Aliprandi, 2005) could be important sources of qualitative information about geomorphological features, such as the presence or absence of glacier lakes, even if they don’t allow precise extraction of shape and area of lakes. Nevertheless, the comparison of topography of the same area on different maps’ edition could be very useful for multi-temporal geomorphological change detection, especially for glaciological purposes (Carton et al., 2003). Pelfini (2004) showed some examples of studies on glacier lakes through the detection and analyses of different phases of their evolution represented in the historical official map of Italy by IGMI.

For the above-mentioned reasons, first actions of our study were the collection, digitalization and georeferencing of topographic maps of the IGMI (1:25,000 in scale) covering the study area and published during the XX century (tab.5.1).

5.2.2 Orthophotos

High resolution orthophotos are proven to be important data sources for glaciological purposes (Salvatore et al. 2015; Smiraglia et al., 2015). The National Geoportal of the Italian Ministry of Environment and Protection of Land and Sea freely provides digital orthophotos, through the Web Map Service (WMS: http://www.pcn.minambiente.it/GN/accesso-ai-servizi/servizi-di-visualizzazione-wms).

Aerial imagery is characterized by a high resolution (ranging from 1:5,000 to 1:10,000 in scale) and usually shows a low or absent cloud coverage. Photos are taken mainly in the summer period when also the snow cover is low or absent.

The analyzed orthophotos have been surveyed in: 1987-1989, 1994-1998, 1998-1999, 2006-2007 and 2012 (tab. 5.1).

Period	Source of data	Scale factor	GSD (m)	σxy (0,2 of the scale factor)	CE95
1929-34	IGMI topographic maps	25,000		5	12.2
1966-70	IGMI topographic maps	25,000		5	12.2
1987-89	OrtHophotos B/W	10,000	1	2	4.9
1994-98	Orthophotos B/W	10,000	1	2	4.9
1998-99	Orthophotos color	10,000	1	2	4.9
2006-07	Orthophotos color	5,000	0.5	1	2.4
2012	Orthophotos color	5,000	0.5	1	2.4

Table 5.1 - List of the data sources, related cartographic parameters and error.

5.2.3 Reports of the annual glaciological surveys

Thanks to the activities of the Italian Glaciological Committee (CGI), the systematic monitoring of Italian glaciers has never been interrupted since it started on 1911. During the annual glaciological surveys, carried out at the end of the ablation summer season, volunteers collect measures, photos and observations of the glaciers and surrounding areas in the Italian Alps. Since 1928, the reports are published in a dedicated section of the CGI Bulletin (CGI, 1928-1977; 1978-2015). CGI members cooperated with the digitalization effort of the Italian Glaciological Committee to offer freely availability of the annual glaciological surveys on the website of the CGI (http://www.glaciologia.it/i-ghiacciai-italiani/le-campagne-glaciologiche/).

5.3 METHODS

Historical maps and digital orthophotos were selected for being used as base layers in an open source GIS (Geographic Information System, Q-gis®) environment. Glacier lakes, with a surface area greater than 100 m^2, were detected and lake outlines manually digitized on computer screen. As buffer polygons for lakes detection, the LIA glaciers extent produced in the framework of the GlaRiskAlp project, available as .kml file from the project website (http://www.glariskalp.eu/?it_inventario-delle-estensioni-attuali-e-passate-dei-ghiacciai,9), were used.

A set of attributes have been assigned to each lake: area, perimeter, elevation, geographic coordinates of the barycenter and detection year. Furthermore, every lake has been classified according to the type of dam, as: bedrock-dammed, moraine/debris-dammed and ice-dammed. The interpretation was supported by the use of TerraExplorer virtual globe. Finally, each lake has been associated to the corresponding alpine supergroup according to the International Standardized Mountain Subdivision of the Alps, ISMSA-SOUISA (Marazzi, 2005).

The large variety of the data sources used (a set of 7 different maps and orthophotos) required consideration of the accuracy of derived data; in particular, the map reading error (σ_{xy} = 0.2 mm of the scale factor) has been considered. In fact, the level of detail of a topographic map and/or a orthophoto is determined by its scale factor. This kind of error approach was decided in order to maintain comparable the planimetric accuracy among different data sources. The final CE95 (Circular Error) has been calculated according to FGDC (1998), AA.VV. (2009) and ASPRS (2014), which considered the 95% of the lake mapping error. Final CE95 values is equal to a supposed real map reading error of 0.49 mm of the scale factor that includes also the uncertainty of manual delimitation. Thus the area precision for each lake has been evaluated by buffering the lake perimeter using the CE95. The overall error of the whole Western Italian Alps lake coverage for each time step (tab. 2) has been assessed by using the root of the squared sum of all the buffer areas, as suggested by Citterio et al. (2007) and Minora et al. (2016).

In addition, the complete set of annual glaciological surveys published by the CGI in the time interval 1927-2014 was analysed to seek further information (description, measures, photos, maps, etc.) on glacier lakes in the Western Italian Alps. All collected data were stored and organized into a dedicated database; other than description text, every single record includes information on: name of the glacier, year of the observation, issue and page of the CGI Bulletin, author of the report. The database represents a useful tool for confirming, integrating and completing results obtained by means of maps and orthophotos analysis and interpretation.

5.4 RESULTS

Here a summary of the results obtained by the analysis and interpretation of topographic maps and orthophotos and by the search of information on glacier lakes on the CGI Bulletin are presented.

Six glacier lake inventories were produced, related to six different time steps: 1930s, 1970s, 1980s, 1990s, 2006-07 and 2012. A general overview of the morphological characteristics of glacier lakes within each of the considered time steps is presented in tab. 5.2. A short description of the results of each inventory is presented below, including numerical data such as the total number of mapped glacier lakes, total lake covered area, altitudinal extent and description of their geographic distribution and the main types of lake.

Year		1930s	1970s	1980s	1990s	2006-07	2012
Number of lakes (N)	Total	43	66	133	178	214	186
Elevation (m a.s.l.)	Mean	2692	2704	2751	2786	2776	2747
	Max	2996	2989	3122	3447	3346	3270
	Min	1868	1868	1868	1868	1868	1868
Perimeter (10^4 m)	Median	0.03	0.03	0.02	0.02	0.02	0.02
Lake surface (10^4 m^2)	Median	0.42	0.38	0.27	0.2	0.2	0.24
	Total	55.58 ± 4	87.64 ±5.18	128.51 ± 2.58	133.37 ± 2.63	145.94 ± 1.39	139.58 ± 1.37

Table 5.2 - General summary of the morphometric characteristics of glacier lakes for the six time steps.

5.4.1 The 1930s

The analysis of IGMI topographic maps dated from 1929 to 1934 has produced an inventory containing 43 lakes. They covered a total area of 55.58 (± 4) · 10^4 m^2 with a median area of 0.42 · 10^4 m^2. The lakes spread out between 1868 m and 2996 m of elevation, their mean elevation was 2692 m a.s.l.

Concerning their geographic distribution about half of mapped lakes (20 over 43 individuals, 47% of the sample) were located in the Rutor-Lechaud chain (Graian Alps), 8 lakes (19%) in the Gran Sassière-Tsanteleina chain (Graian Alps) and the other 15 lakes (34%) spread out from the Ambin-Ciamarella chain (Cottian and Graian Alps) to the Monte Rosa group (Pennine Alps). No lakes have been identified in the Lepontine Alps.

Concerning the lake types, the great majority were proglacial lakes located in bedrock overdeepenings (33 individuals, 77% of the sample), some being dammed by moraines (10 individuals, 23% of the sample). Only 4 lakes (9% of the total sample) were in contact with the glacier front, such as the proglacial lake at the Monciair Glacier, Gran Paradiso chain, Graian Alps (fig. 5.1).

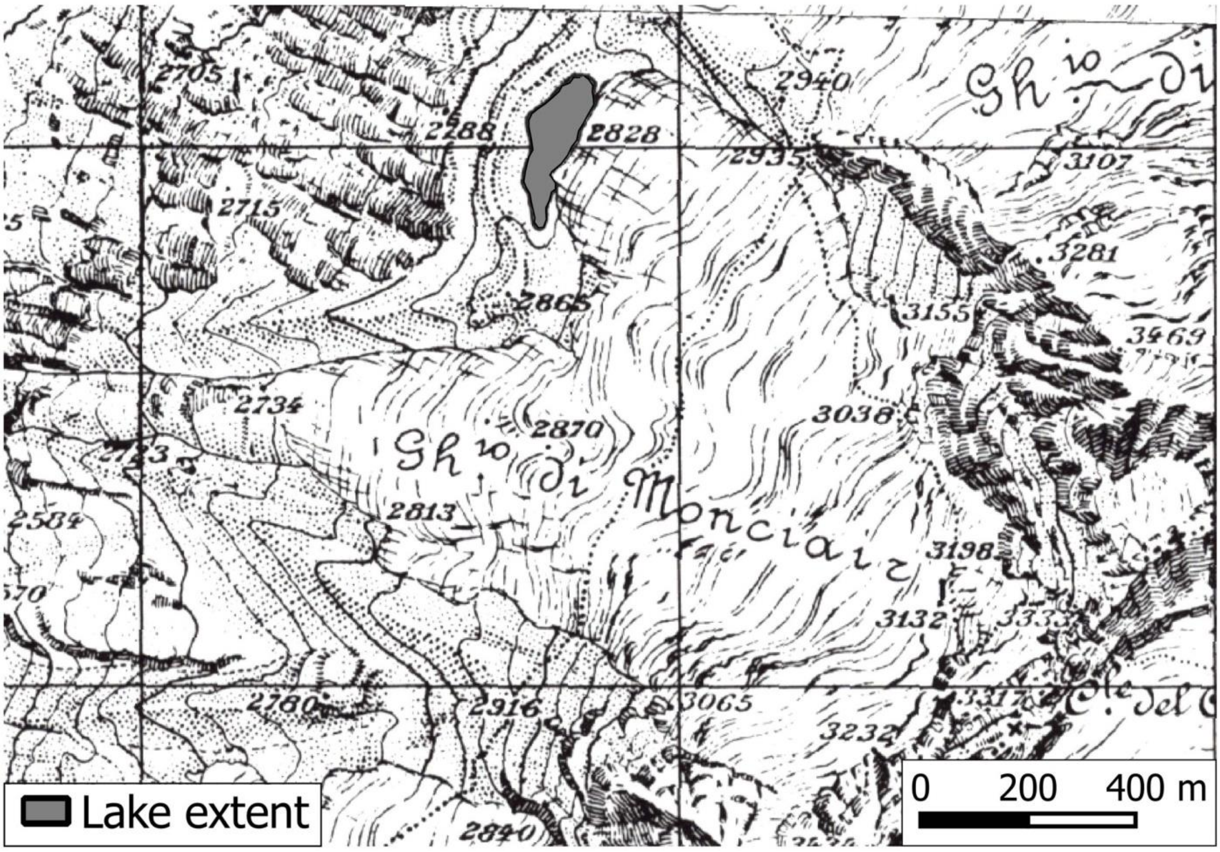


Figure 5.1 - Monciair Glacier (Gran Paradiso Chain, Graian Alps) and its proglacial lake on the IGMI sheet 41 II NO, Ceresole Reale (1931).

Almost all the lakes identified on the first edition of the IGMI topographic map have been recognized also in further maps and orthophotos, thus possibly surviving about 80 years. Only 2 lakes constitute an exception: they were mapped in the 1930s but not recognized in the following documents.

According to the reports of the CGI, in 1933 the drainage of the Galambra Lake (fig. 5.2) took place. The event was also described by Peretti (1935). The water level lowered by 14 m and the areal dimension of the lake changed from 422 x 222 m to 62 x 28 m.

Figure 5.2 - Evolution of the Galambra Glacier and its lake through the XX and XXI centuries: a) historical photo by the IGM taken in 1900; b) historical postcard travelled in 1954; c) photo taken during the glaciological survey in 2011 by the CGI volunteer Tron.

5.4.2 The 1970s

The analysis of the successive edition of the IGMI map (issued between 1966 and 1970) allowed identification of 66 glacier lakes. The total area covered by the lakes was 87.64 (±5.18) · 10^4 m^2 (median 0.38 · 10^4 m^2). The elevation ranged from 1868 m to 2989 m, with a mean altitude of 2704 m a.s.l.

Lakes were located mainly in the Rutor-Lechaud chain (27 lakes, 41% of the sample) and in the Monte Rosa group (20 lakes, 30% of the total sample). They were proglacial lakes (78% dammed by the bedrock and 22% by moraine).

Some of the largest lakes of the study area were mapped for the first time in the 1970s, they are the lakes located at the Valtournanche (about 100000 m^2), Locce Nord (57000 m^2), Tzere (about 36000 m^2, fig. 5.3) and Rutor (about 29000 m^2) glaciers. Their formation took place between the 1930s and the 1970s. Bulletins of the CGI report, for example, that the Locce Lake was described for the first time in the 1941 glaciological survey.

Figure 5.3 - The new formed lake at the Tzere Glacier, the photo was taken by the CGI volunteer Cotta Ramusino in 1976 during the annual glaciological survey.

5.4.3 The 1980s

The observation of the orthophotos related to the 1987-89 national flight allowed to identify 133 glacier lakes within the study area. Lakes covered a total surface of 128.51 (± 2.58) $\cdot 10^4 m^2$ (median $0.27 \cdot 10^4 m^2$). Their altimetric distribution ranged between 1868 m and 3122 m, their mean elevation was 2751 m a.s.l.

The majority of lakes were located in the Rutor-Lechaud chain (32%), Gran Sassière-Tsanteleina chain (13%), Monte Rosa group (12%) and Gran Paradiso chain in the Graian Alps (11%).

Lakes were proglacial lakes dammed by the bedrock (73%) or by moraine (26%). A supraglacial lake was detected on the surface of the Schiantala Glacier (fig. 5.4), a debris-covered glacier in the Corborant-Tenibres-Enciastraia Chain (Maritime Alps).

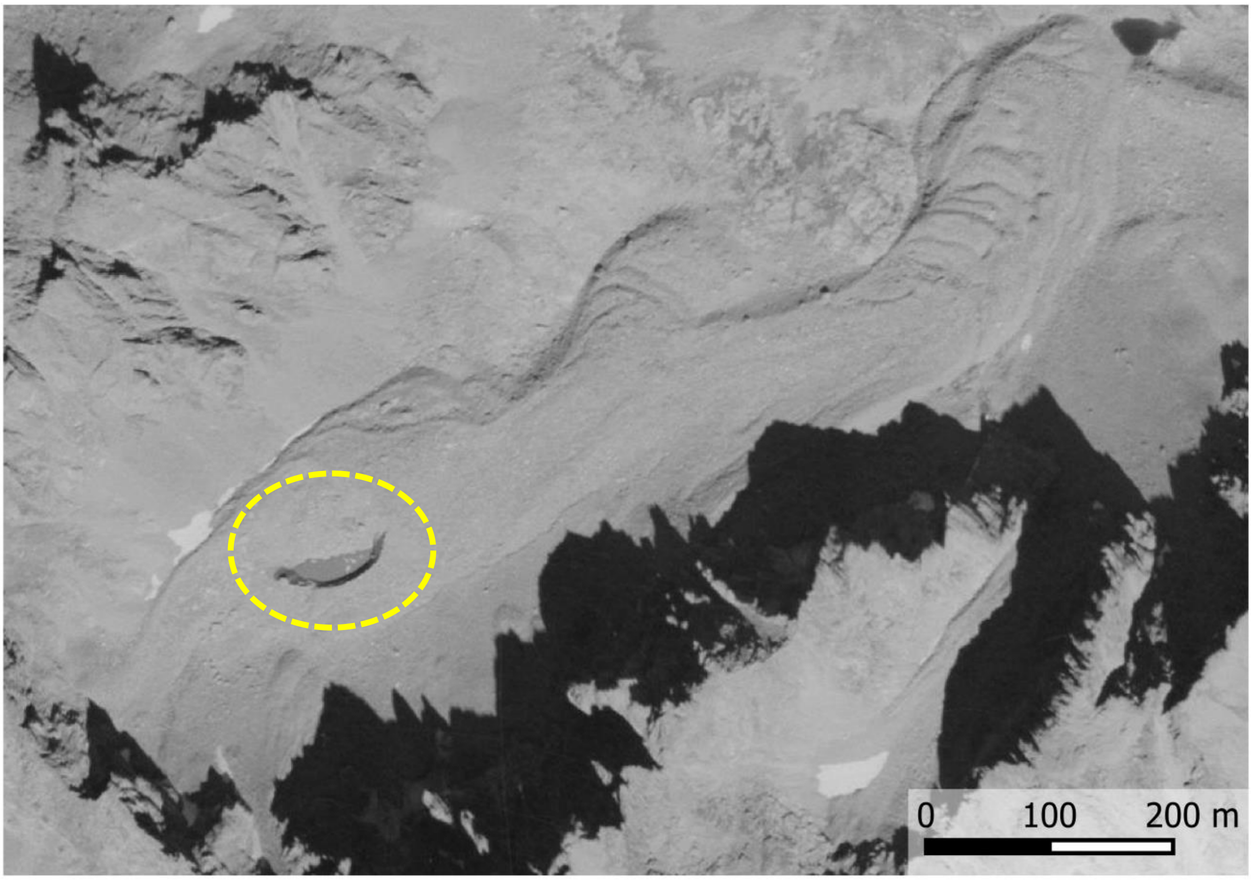


Figure 5.4 - Schiantala debris-covered glacier and the new formed supraglacial lake (yellow dotted circle) on the 1988-89 orthophotos (Imagery: Italian National Geoportal).

On the 1987-89 orthophotos was for the first time possible to detect and map the large lake at the Goletta Glacier which measured about 90000 m^2.

The most interesting phenomena happened between the end of the 1970s and the beginning of the 1980s were the repeated drainage of the Locce Lake (1970, 1978, 1979). Successively, the water level was artificially lowered by cutting the moraine and pumping the water out of the dam (Tropeano et al., 1999).

5.4.4 The 1990s

Concerning the time period between 1994 and 1999, 178 glacier lakes were mapped covering a total area of 133.37 (± 2.63) $\cdot 10^4$ m^2 (median 0.20 $\cdot 10^4$ m^2). Their minimum elevation was 1868 m, the maximum 3447 m and the mean 2786 m a.s.l.

Glacier lakes were located mainly in the Rutor-Lechaud chain (30%), in the Gran Sassière-Tsanteleina chain (13%), in the Gran Paradiso chain (12%) and in the Monte Rosa group (10%). They were mainly proglacial lakes filling bedrock overdeepenings (75%) and dammed by moraine or debris (26%). There were also few cases of supraglacial lakes (2%) located on the surface of debris covered glaciers.

During the 1990s the lake at the South Entrelor Glacier formed covering an area of about 6000 m^2, in the next inventories its surface tripled.

Between the end of the XX and the beginning of the XXI century some of the most dangerous and studied lakes formed: in 1999 the lake at the Croce Rossa Glacier (fig. 5.5), in 2001 the lake at the Rocciamelone Glacier and the Effimero Lake on the Belvedere Glacier.

Figure 5.5 - The new formed lake at the Croce Rossa Glacier in 1999 (ph. Mercalli).

5.4.5 2006-07

High quality of the orthophotos allowed improved data collection and more detailed analysis related to the years 2006-07. 214 glacier lakes were identified, with a total area of 145.94 (± 1.39) $\cdot 10^4\,m^2$ (median $0.20 \cdot 10^4\,m^2$). Lake area varies between a minimum of about $0.01 \cdot 10^4\,m^2$ to a maximum of $12 \cdot 10^4\,m^2$. Half of the lakes were characterized by an area smaller than $0.2 \cdot 10^4\,m^2$ and 76% of the lakes have a surface area less than $0.6 \cdot 10^4\,m^2$ (fig. 5.6).

The elevation varies between 1868 m and 3346 m and the mean value is 2776 m. In the years 2006-07, 72% of the lakes were located between 2600 and 3000 m a.s.l (fig. 5.7).

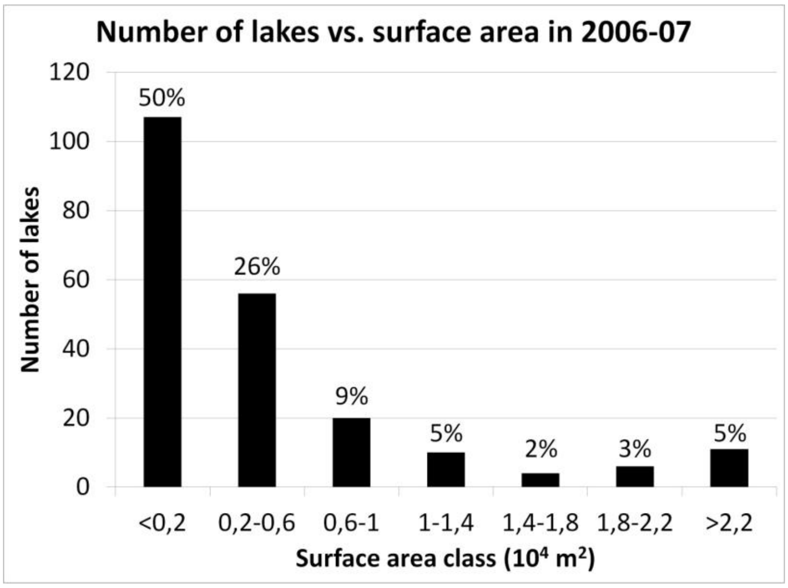


Figure 5.6 - Frequency distribution of glacier lakes in 2006-07 with respect to their surface area.

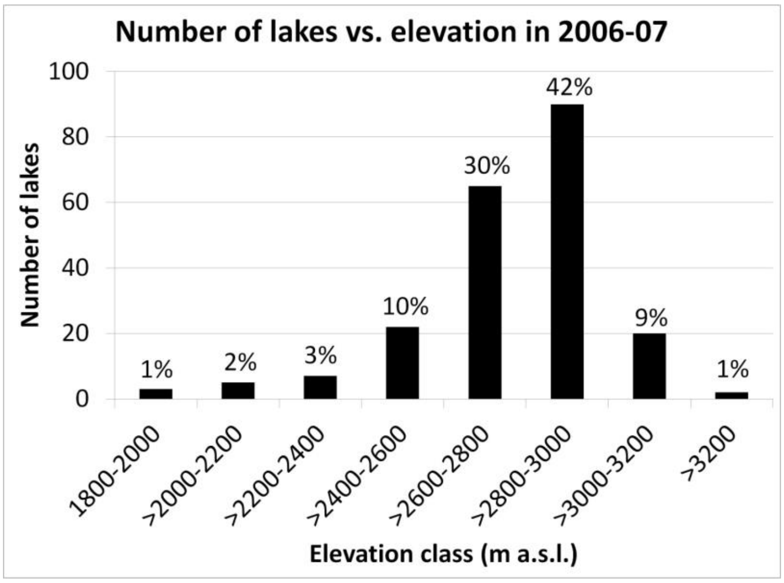


Figure 5.7 - Frequency distribution of glacier lakes in 2006-07 with respect to their elevation.

Glacier lakes of the 2006-07 inventory were localized mainly in the Rutor-Lechaud chain (27%), in the Gran Sassière-Tsanteleina Chain (15%), in the Gran Paradiso chain (13%) and in the Monte Rosa group (12%).

From South to North, the mountain arch of the Western Italian Alps encompasses approximately 250 km (only about 77 km from West to East). Within the 2006-07 sample of glacier lakes in the Western Italian Alps, their geographical distribution was analysed by considering elevation as a function of latitude (fig. 5.8). Glacier lakes in the Maritime Alps were located around 2600 m a.s.l.; in the Cottian Alps between 2800 and 3000 m of elevation, with the exception of a lake in the Monviso Group located at 3270 m a.s.l.; in the Graian Alps they were mainly located between 2400 and 3200 m, with the exception of the lakes at the Miage Glacier located at much lower elevation (about 1900 m); in the Pennine Alps there was a wide range of elevations of glacier lakes ranging from 2100 m (lakes on the Belvedere Glacier) to a maximum of 3300 m a.s.l.; in the Lepontine Alps glacier lakes have been surveyed between 2300 and 2800 m a.s.l.

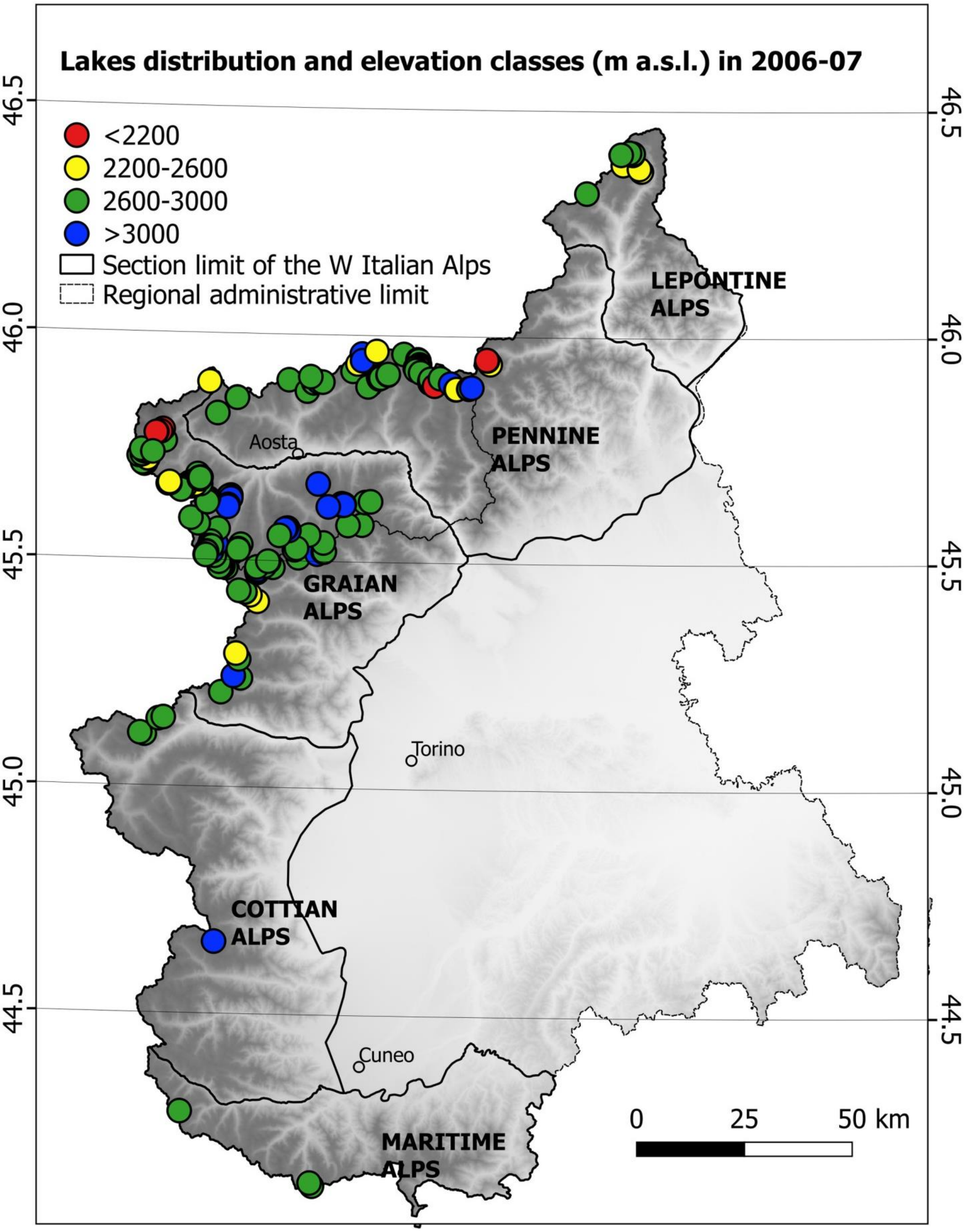


Figure 5.8 - Maps of the geographical and altitudinal distribution (m a.s.l.) of glacier lakes in 2006-07.

5.4.6 2012

On the set of orthophotos dated 2012, 186 glacier lakes have been identified. Lakes covered a total area of 139.58 (± 1.37) $\cdot$ 10^4 m^2 (median 0.24 $\cdot$ 10^4 m^2). Decrease of both the total number and total area of glacier lakes in 2012 with respect to the previous inventory (2006-07) is unexpected, in particular because glaciers continued to retreat. The reason of this difference is probably do to the data source: the 2012 orthophotos were taken in the first half of July 2012, when the snow cover was considerably extended on the investigated areas (13%); this prevented to understand whether some lakes (32) survived or disappeared.

Glacier lakes were located between 1868 m and 3270 m of elevation (mean value: 2747 m a.s.l.).

Glacier lakes were located in the Rutor-Lechaud chain (27%), in the Gran Paradiso chain (14%), in the Gran Sassière-Tsanteleina chain (12%) and in the Monte Rosa group (12%).

Concerning the lake types: 69% were dammed by the bedrock, 26% were dammed by moraine or debris and 5% were supraglacial lakes on debris-covered glaciers such as the Miage and the Belvedere glaciers.

Moreover, on the 2012 orthophotos the new lake at the Lys Glacier can be detected (fig 5.9). The lake embedded in the dead ice melting in the proglacial area of the Lys Glacier was of big concern because of its increasing dimension.

Figure 5.9 - The new lake formed in the dead ice melting in the proglacial area of the Lys Glacier (2012).

5.4.7 Database of the reports of the glaciological surveys concerning glacier lakes

The information on glacier lakes derived from the reports of the annual glaciological surveys published by the CGI was stored in a dedicated database. 762 records from reports of the time period 1927-2014 were inserted. Considered reports are short or long description of glacier lakes observed by the volunteers of the CGI during their survey at glaciers, sometimes associated with measurements, photos and maps of lakes.

The number of reports on glacier lakes for each year varies depending on the total number of glaciers surveyed; for example, during the Second World War only few glaciers were visited, therefore also the number of reports on lakes was low. Starting from the beginning of the 21st century the number of reports increased (fig. 5.10). This fact could be attributed both to the increase in the number of glacier lakes and to the greater attention of the volunteers to this kind of phenomenon.

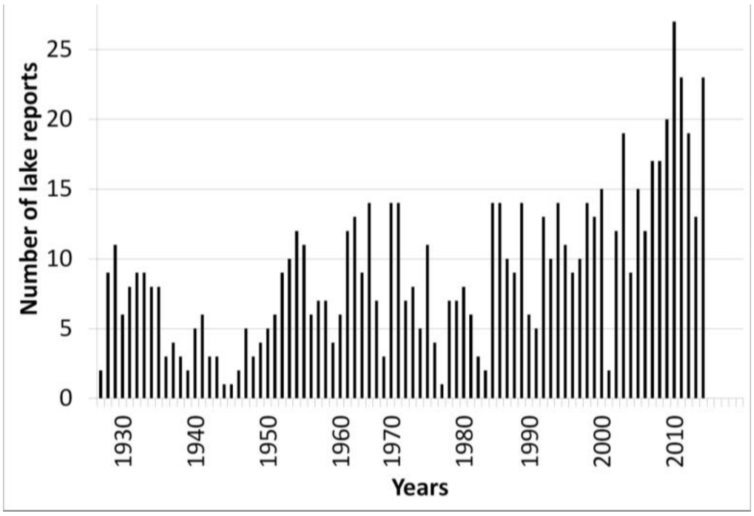


Figure 5.10 - Number of reports regarding lakes stored in the database for each annual glaciological survey.

Information about glacier lakes are related to 129 glaciers of the Western Italian Alps, 24 of them have more than 10 years of reports regarding the presence of lakes in their surroundings (tab. 5.3). For example, glaciers of Rutor (42), Miage (34), Locce Nord (34), Goletta (31) and Valtounanche (30) have a series of more than 30 years of reports regarding the presence of lakes. Having such long series of information allows to reconstruct the evolutionary stages of this dynamic system during a long time period (e.g.: the first notice about lakes at the Rutor Glacier dated 1928 and the last one 2014).

Glacier	N of reports	First report	Last report
Pera Ciaval	12	1991	2014
Bessanese	24	1928	2013
Mulinet Sud	10	1957	2012
Sengie Sett.	14	1971	2014
Lauson	14	1931	2007
Monciair	12	1959	2005
Lavassey	24	1928	2014
Soches-Tsanteleina	11	1951	2011
Goletta	31	1948	2011
Rutor	42	1928	2014
Valaisan	10	1951	2014
Chavannes	15	1952	2002
Miage	34	1929	2014
Cherillon	11	1943	1981
Valtournanche	30	1931	1980
Lys	16	1970	2014
Indren	11	1953	2014
Locce Nord	34	1934	2013
Belvedere	13	1993	2014
Gemelli di Ban	10	1961	1987

Table 5.3 - Glaciers with more than 10 records concerning their lakes.

6 POTENTIAL FUTURE LAKES IN THE AOSTA VALLEY RESULTING FROM CONTINUED GLACIER SHRINKAGE

6.1 SPECIFIC OBJECTIVES

The main goal of the present chapter is to provide a general outlook of potential future glacier lakes in the Aosta Valley, a newly investigated region for the application of the GlabTop2 model. It also suggests new modes for the validation of corresponding results, not only at the local scale as a forward validation, but also at the regional scale as a backward validation, as summarized in fig. 6.1.

Specific objectives to be achieved are:

- to give an estimation of the ice thickness and volumes of Aosta Valley glaciers;
- to provide a map of possible future lakes for the test region;
- to validate, through both well established and new ways, the suitability of the GlabTop2 for anticipating the formation of lakes and for modelling glacier-bed overdeepenings for mountain glaciers;
- to test the sensitivity of the model on the input data.

STEP	INPUT DATA	METHOD
1. Modeling glacier ice thickness	Glacier outlines 1991 DEM 1991	Glacier Bed Topography Model 2 (Frey et al., 2014)
2. Modeling bedrock topography and overdeepening locations	DEM 1991 Ice thickness distribution (raster file)	ArcGis Toolbox (Linsbauer et al., 2012)
3. Backward validation at the regional scale	Modeled overdeepenings Lake inventories (Chapter 5)	Comparison between modelled and real lakes in areas set free by the glaciers between 1991 and now
4. Backward validation at the local scale	Modeled bedrock Real bedrock (LIDAR 2008)	Comparison between modelled and real bedrock along selected profiles in 2008 glacier free areas
5. Forward validation at the local scale	Modeled bedrock GPR data on specific glaciers	Comparison between modelled and measured bedrock along selected profiles
6. Forward validation at the regional scale	Modeled overdeepenings Orthophotos DEM 1991	Morphological criteria (Frey et al., 2010a)
7. Sensitivity test	DEM 1991 at different resolution	Repeat steps 1, 2, 3 and 5

Figure 6.1 - Work flow of the present chapter.

6.2 FOCUS ON THE AOSTA VALLEY AS TEST REGION

The present chapter focuses on the glacierized areas of the Aosta Valley Region within the Western Italian Alps. The Aosta Valley is recognized as the region with largest glacier-covered area of Italy. According to the New Italian Glacier Inventory (Smiraglia et al., 2015), related to the 2005-2011 period, 192 glaciers exist in the Aosta Valley Region with a cumulative area value of 133.73 km^2, which corresponds to the 36% with respect to the whole Italian coverage (21% with respect to the total number). In 1991, the year of the dataset used for the modelization, there were 183 glaciers (> 0.05 km^2) covering 163,1 km^2 (fig. 6.2). Glaciers were less in number but they covered a larger area with respect to 2005-2011. Differences in number and area have to be attributed to fractioning processes (from one single glacier body to two or more smaller bodies) and shrinkage and disappearance that took place in the meantime.

The largest glaciers were: Miage (13.6 km^2), Lys (11.8 km^2) and Rutor (9.3 km^2).

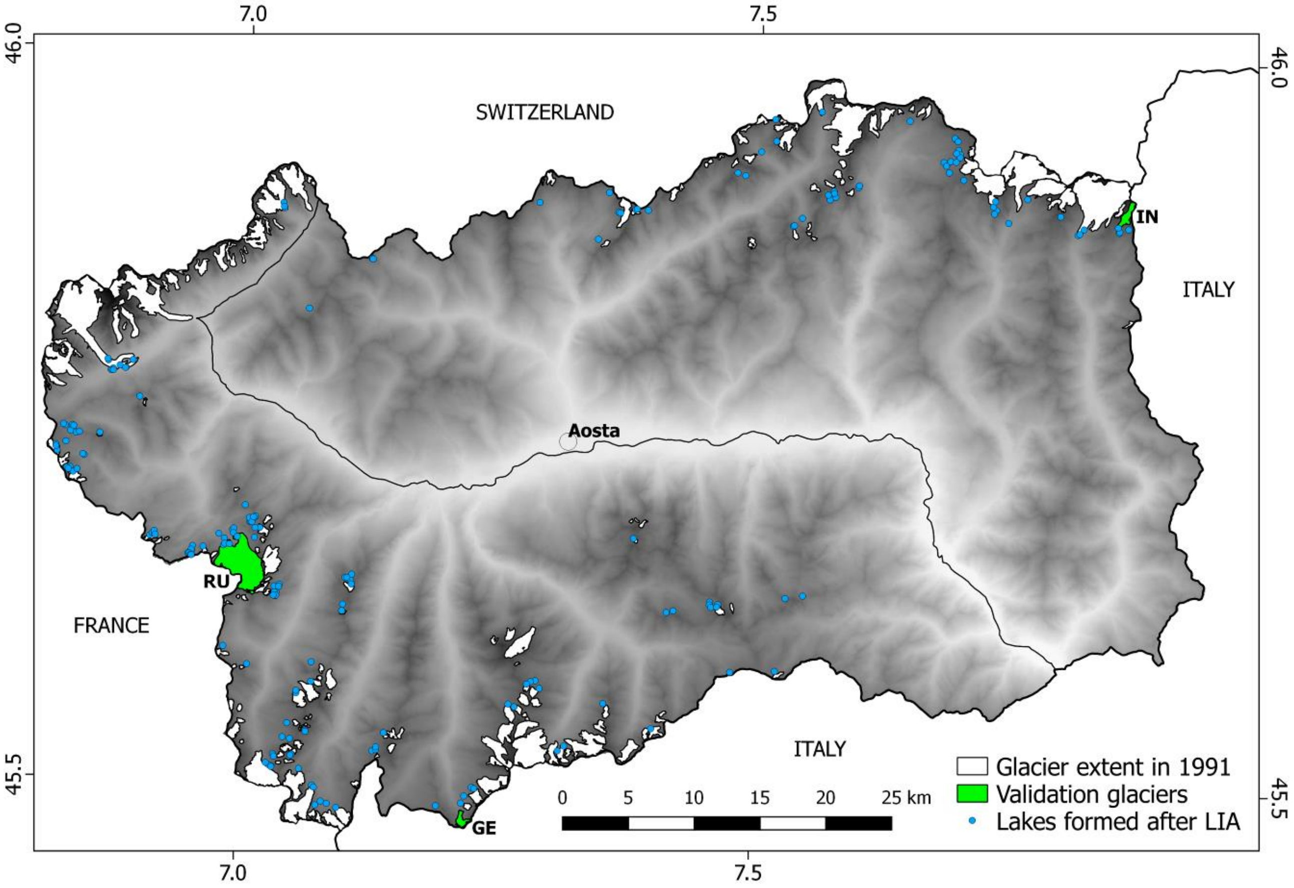


Figure 6.2 - Map of the study region showing all Aosta Valley glaciers and all glacier lakes formed after the end of the Little Ice Age. Initials refer to the validation glaciers: Indren (IN), Rutor (RU) and Gran Etret (GE).

Glaciers stretch from about 1400 m a.s.l. up to 4800 m a.s.l and a mean elevation of about 3000 m a.s.l.. The 15 glaciers with an area larger than 3 km^2 contribute 54% to the total glaciated area but only 8% to the total number. On the contrary, glaciers smaller than 1 km^2 account for 80% of the number but only 23% for the area (fig. 6.3). Most glaciers are mountain glaciers with few cases of valley glaciers, in 1991 (i.e.: Miage Glacier, Brenva Glacier, Lys Glacier, Verra Grande Glacier, Pré de Bar Glacier).

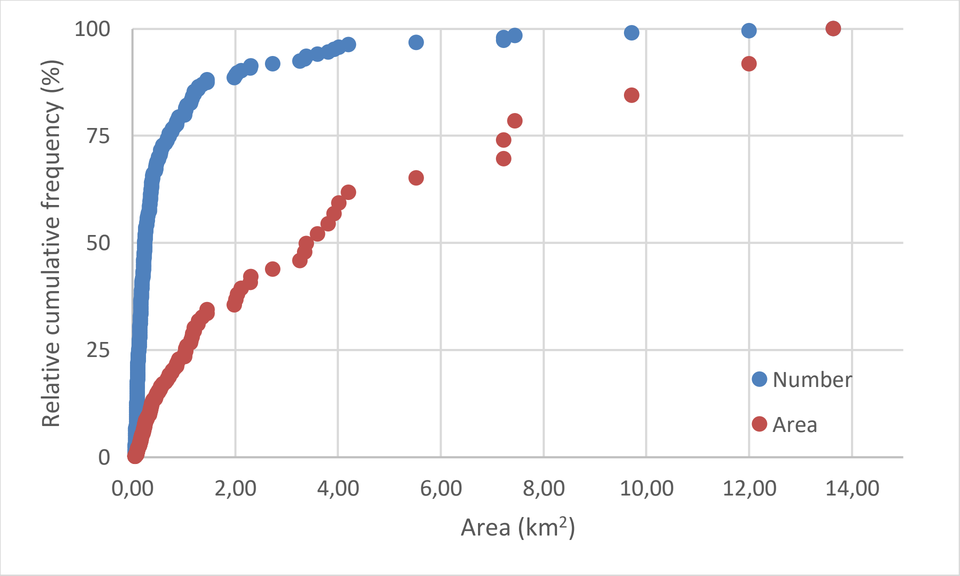


Figure 6.3 - Plot showing the glacier area and the number of glaciers with respect to the relative cumulative frequency of both values.

Within the study region, as reported in the previous chapter, about 200 new glacier lakes appeared within LIA glacier extent boundaries covering an area of about 1.3 km^2 and about ¾ of them being dammed by bedrock. The 12 lakes with an area larger than 20,000 m^2 contribute 52% to the total lake coverage but only 6% to the total amount. On the other hand, lakes smaller than 6000 m^2 account for 81% of the number but only 23% for the total area.

Glacier lakes represent both opportunities and hazards in the study region. Lakes such as the Miage lake, are important tourist attractions in addition to be valuable geosites (e.g. Lago Blu at Verra Glacier in Ayas Valley). There are also some examples of lakes that have an associated potential hazard, i.e. Rutor (Dutto & Mortara, 1992) and Miage (Diolaiuti et al., 2006) lakes and more recently the outburst flood event, occurred in August 2016, at the Gran Croux lake above Cogne (Gran Paradiso group) has to be mentioned (FMS, 2016).

Besides being an important region for numbers of glaciers and lakes, the Aosta Valley was chosen also for its large amount of available data on this topic. Information about past (Ajassa et al., 1994; 1997; CGI-CNR, 1961; Citterio et al., 2007; Diolaiuti et al., 2012; Giardino et al., 2017) and present (Smiraglia et al., 2015; Salvatore et al., 2015) glacier extent and surface elevation are available and fundamental as input data for the model. Existing and available glacier-lake inventories (form the previous chapter) and GPR data (Villa et al., 2008) are useful for validating model results.

Three glaciers (Gran Etret, Indren and Rutor) were selected for validation of the model results with GPR data. Gran Etret Glacier (0.6 km^2) is in the Gran Paradiso chain of the Graian Alps. It is a simple basin mountain glacier facing N. It lost about 75% of its LIA coverage. Indren Glacier (1 km^2) is a simple basin mountain glacier, facing S and located in the Monte Rosa group in the Pennine Alps. The slope is quite steep, except the central part of the glacier, which is more flat compared to the surroundings. The glacier front retreated about 1 km after the end of the LIA, 4 glacier lakes appeared dammed by the glacially modelled bedrock. Rutor Glacier (9.1 km^2 in 1991) is located in the Rutor-Lechaud chain in the Graian Alps, facing NW. It is the third glacier in Aosta Valley considering its area extension and has a quite flat surface morphology. Rutor Glacier is divided into two main fluxes by a rock ridge, the conjunction of the two fluxes is visible in the lower part of the glacier, down valley a rock outcrop where a medial moraine forms. The glacier has a well-known history of a series of glacier lake outburst floods between 1430 AD and 1864 AD due to front fluctuations (Orombelli, 2005). After the end of the LIA, 8 new lakes have formed dammed by moraines and in newly exposed overdeepenings (Villa et al., 2007).

6.3 DATASETS AND METHODS

6.3.1 The GlabTop2 approach applied to all Aosta Valley glaciers

The Glacier Bed Topography model version 2 (GlabTop2 model; Frey et al., 2014) is fully automated and requires a minimum set of input data: glacier outlines and a surface digital elevation model (DEM).

It allows to model glacier bed-topography over large areas combining digital terrain information and slope-related estimates of glacier thickness (Linsbauer et al., 2016). Consequently, the location of possible overeepenings can be assessed.

Ice thickness (h) is calculated for an automated selection of randomly picked DEM cells within the glaciated area by using

$$h = \tau / (f\ \rho\ g\ \sin\alpha)$$

τ is the basal shear stress, f the shape factor (related to the friction of a real glacier with the valley walls), ρ the ice density (900 kg m^{-3}), g the acceleration due to gravity (9.81 ms^{-2}) and α the surface slope (which is calculated by the model on randomly selected cells).

The calculation requires estimating the parameters τ and f. Generally, as showed in previous works (Haeberli & Hoelzle, 1995; Linsbauer et al., 2016; Farinotti et al., 2017), τ is parameterized with the vertical extent ΔH by the equation $\tau=0.005+1.598\Delta h-0.435\Delta h^2$ and f is set to 0.8 for all glaciers which is typical for valley glaciers. Farinotti et al. (2017) show that good performances are given by this set of parameters for mountain glaciers (Brewster, Kesselwandferner, Urumqi) and, less, for cirque glaciers (Washmawapta Glacier) as those of the present study region. The model was run setting the above-mentioned parameters as suggested in the literature. The resulting ice thickness distribution can be subtracted from the corresponding surface DEM to provide the bed topography of the investigated glaciers.

In the present research, the regional DEM of 1991 provided by the Regione Autonoma Valle d'Aosta (RAVA) with an original spatial resolution of 10 m, produced from aerial photographs was used. The DEM was down-sampled to 60 m for the calculation using the bilinear interpolation algorithm, this in order to avoid influence of small-scale surface morphologies on model outputs as suggested by Farinotti et al. (2017). As glacier outlines, the .kml file available on the GlaRiskAlp Project website (http://www.glariskalp.eu) and related to 1999 was used. The outlines were modified and adjusted to the beginning of the 1990s, analysing the DEM and available orthophotos of 1988-89, in order to have a good fit with the DEM. Glaciers smaller than 0.05 km^2 have been removed in order to avoid inaccurate results, as suggested by Linsbauer et al. (2016), because they are subjected to high uncertainties. The model was applied to all the glaciers of the study region assessing, firstly, the ice thickness and consequently the DEM of the bedrock underneath present glaciers. A shape file of the modeled overdeepenings with associated morphological parameters (area, depth, volume) was produced.

6.3.2 A new procedure for validating model results: the backward approach

Steps 2 and 3, as presented in fig. 6.1, synthesizes the proposed backward approach.

It is based on the assumption that in these area left by glaciers from the 1990s (year at which the DEM used refers) until now, new glacier lakes appeared and glacially sculpted morphologies become exposed because of glacier retreat. Following a backward-looking approach, existing glacier lake inventories related to the end of the 1990s, 2006 and 2012 (chapter 5) can be used to verify the real presence of modeled lakes at the regional scale.

Moreover, at the local scale, always considering areas subject to glacier retreat until the 1990s, it is possible to compare their real topography with the modeled one by GlabTop2 along selected profiles. However, it has to be considered that ice thickness estimates at glacier margins are especially uncertain because of problems with slope calculation. The real topography is represented by the regional LIDAR of 2008.

Using DEMs and glacier outlines from the past (in the case of this research related to the 1991) allows to compare the results of the model (potential lakes and bedrock topography) with the real situation as it appeared after the glacier retreat occurred in the years between the survey of the input data and now. The real situation is well represented by the lake inventories and the new DEMs.

6.2.3 The well-established ways for validating model results: the forward approach

As already described in chapter 2, researchers used geophysical investigations carried out on selected glaciers in order to validate model results.

A forward-looking validation is performed comparing Ground Penetrating Radar (GPR) profiles with modeled bedrock at the glacier scale (step 5 in fig. 6.1). Existing GPR data at Rutor and Gran Etret glaciers have been provided by the work of Villa et al. (2008) and by RAVA in collaboration with the Department of Environment, Land and Infrastructure Engineering (Politecnico di Torino), respectively. They were acquired during different field campaigns (Rutor: 1996 and 2006, center frequency 35 MHz; Gran Etret: 2013 by helicopter, center frequency 70 MHz). A GPR survey was also carried out during summer 2016 (center frequency 200 MHz) on the central area of Indren Glacier where GlabTop2 shows the presence of a possible subglacial overdeepening (20m run).

Morevoer, the morphological criteria proposed by Frey et al. (2010) can be used as a forward validation at the regional scale (Colonia et al., 2017). For each modeled overdeepening of the test area it is possible, using orthophotos and DEMs, to verify if its location corresponds with the mentioned criteria (step 6).

6.3.4 Sensitivity test on input data

Different runs of GlabTop2 were performed varying the pixel size of the input data from a high to a low spatial resolution: 20 m, 40 m, 60 m and 90 m (step 7). The objective is to evaluate the effect of the change of the pixel size on model results (ice thickness, bedrock geometry, total overdeepenings, depth and area), considering that this second version of GlabTop does calculation for an automated selection of randomly selected DEM cells.

6.4 RESULTS

6.4.1 Thickness and volume of the Aosta Valley glaciers

GlabTop2 was applied to the 1991 DEM (60 m spatial resolution) with the glacier outlines adjusted to 1991, as described before. In figure 6.4 the ice thickness distribution for all Aosta Valley glaciers is shown.

Ice thicknesses lower than 50 m are prevalent. 56% of the glaciers have a mean ice thickness below 25 m and another 31% between 25 and 50 m.

A total ice volume of 7.3 ± 2.2 km^3 was estimated, considering 30% as the uncertainty of the model as demonstrated by Linsbauer et. al. (2012). The arithmetic mean ice thickness, obtained by dividing the total volume by the total area, is about 45 m. Themaximum value of the ice thickness is 230 m.

Considering the volume of the single glaciers, the 3 largest glaciers contained 27% of the total volume, the 8 largest 50% and the 23 largest (12% by number) 78%.

The three largest glaciers are: Miage (0.71 km^3), Rutor (0.65 km^3) and Lys glaciers (0.6 km^3). The thickest (considering the mean thickness) are Rutor (71 m), Tribolazione (65 m) and Pré de Bar (61 m).

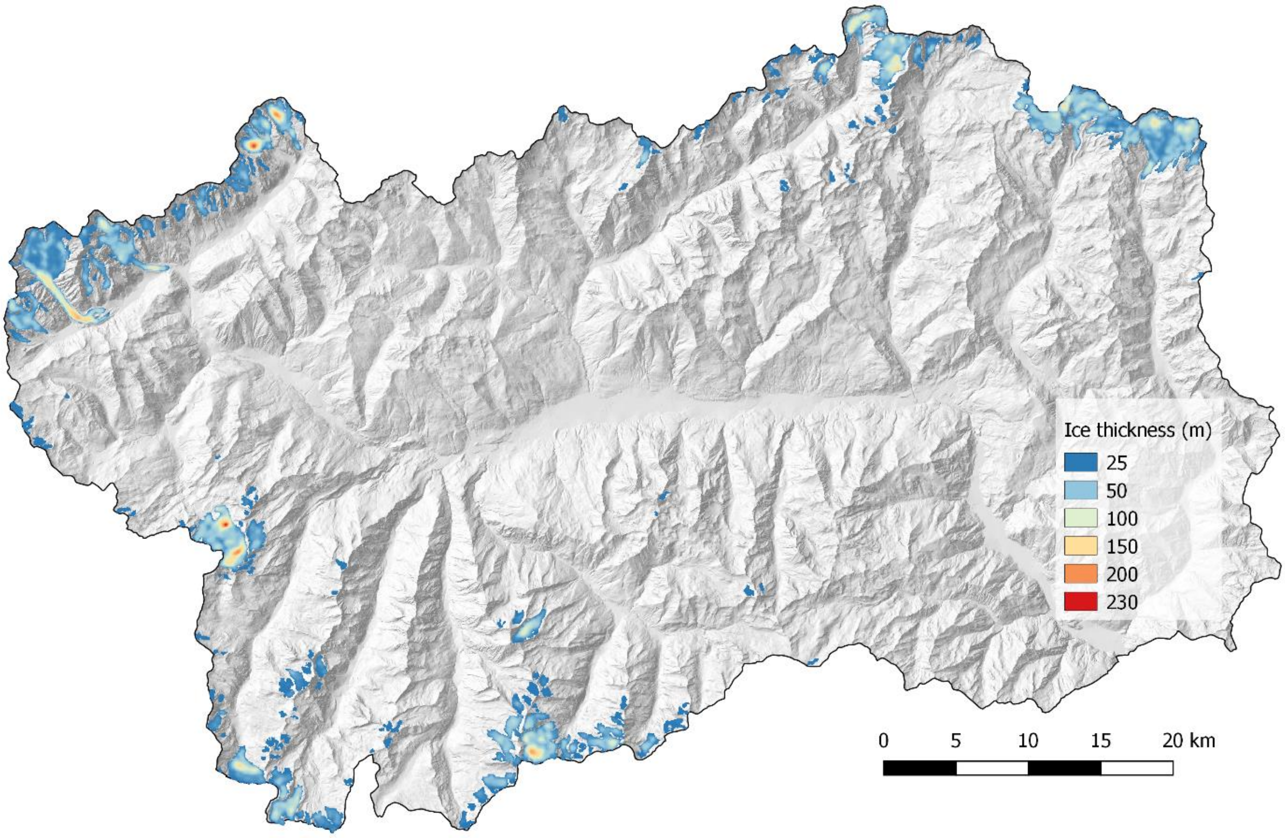


Figure 6.4 - Ice thickness distribution as modeled with GlabTop2 for all Aosta Valley glaciers.

6.4.2 Possible future lakes

The total number of detected overdeepenings, using a threshold of 1 ha (10,000 m^2) for the lakes area, is 46. Figure 6.5 shows the location, mean depth and area of the overdeepenings located in the most important glacierized areas of the study region. Overdeepenings are located in flat regions (slope < 5°), in fact, it has to be noticed that for the steepest mountain glaciers located for example in the Monte Bianco massif no overdeepenings have been modeled. About 3.1 ± 0.9 km^2 of potential future lakes can appear with a corresponding total volume of 0.06 ± 0.02 km^3, which is less than 1% of the total glacier volume. The mean arithmetic depth is about 18 m (weighted with the total area).

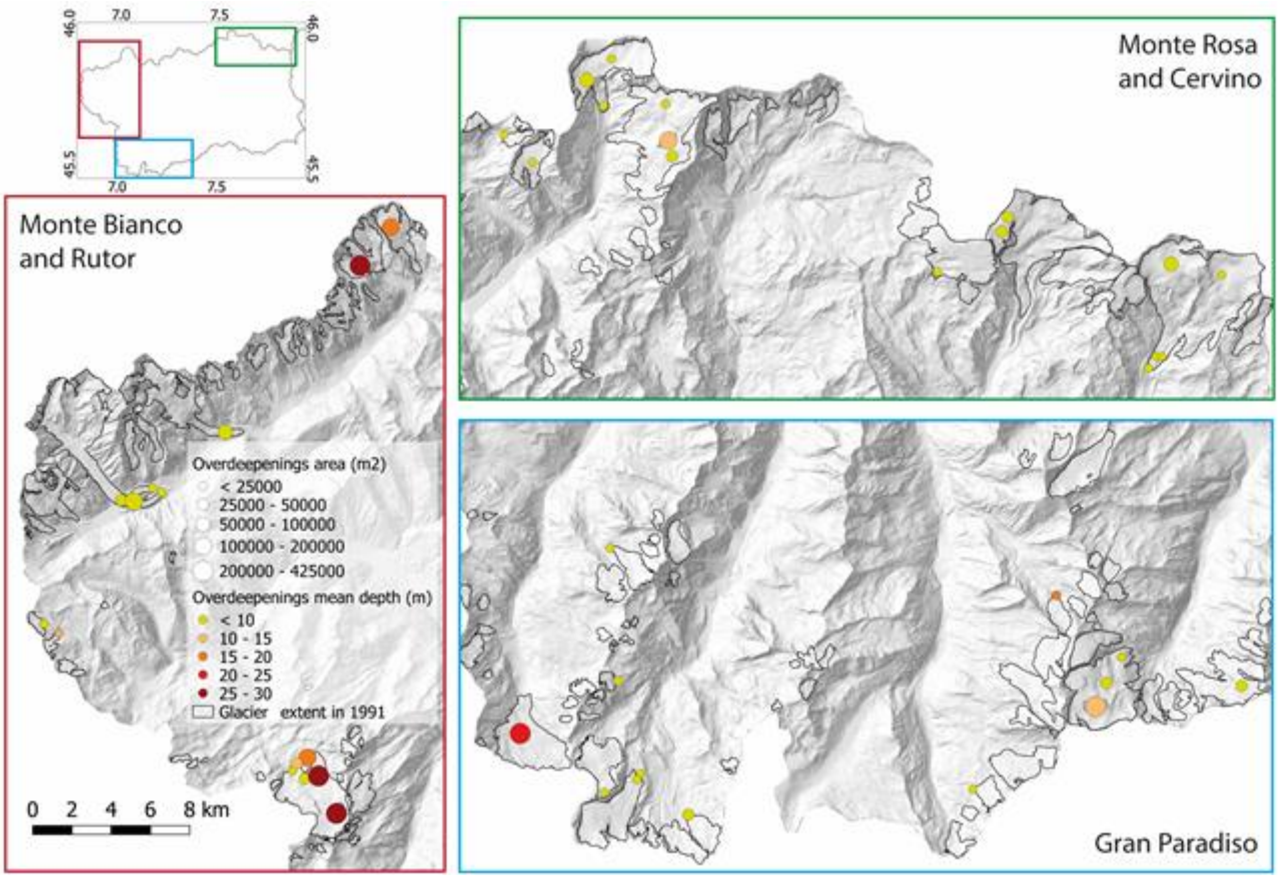


Figure 6.5 - Location of modeled overdeepenings for the main massifs of the Aosta Valley Region. The size of the points refers to the area of the overdeepening and the color to the mean depth.

A mean modeled overdeepening has an area of 68,000 m^2 and a volume of 1.2 · 10^6 m^3.

7 modeled overdeepenings larger than 1 · 10^6 m^3 counted for the 89% of the total volume and 2 larger than 10 · 10^6 m^3 for the 45%. These last two modeled overdeepenings are located underneath the Rutor (425,000 m^2 and 12.6 · 10^6 m^3) and the Triolet (360,000 m^2 and 12.2 · 10^6 m^3) glaciers.

Considering the distribution of the overdeepenings, the majority are located in the Monte Rosa-Cervino massif, which are also the shallower of the study area. They are characterized by a mean depth lower than 10 m. In the Monte Bianco massif, if Miage and Rutor glaciers are excluded, there are few overdeepenings due to morphology of the remaining glaciers that are the steepest of the study area.

In general, the overdeepenings are located either at the front of the glaciers or in the wide and flat accumulation area.

6.4.3 Backward and regional validation

Between the 1990s and now, glaciers have retreated in the whole study region, glacially sculpted landscapes became exposed and new lakes formed. As a backward-looking validation, the overdeepenings located in those areas left by the glaciers between the 1990s and 2012 were considered and compared with the existing lakes.

The focus is on:

- existing lakes also modeled by GlabTop2;
- existing lakes not being modeled;
- modeled overdeepenings not corresponding to real lakes (false positive).

In the considered time period, according to the information collected in the previous chapter, 35 lakes appeared in areas left by glaciers, their area varies from a minimum of 300 m^2 to a maximum of about 50,000 m^2. There are only six lakes greater than 10,000 m^2 (large lakes), seven have an area between 5000 and 10,000 m^2 (medium lakes) and 22 are smaller than 5000 m^2 (small lakes). In the same areas 16 overdeepenings (> 10,000 m^2) have been modeled.

9 (26%) of the 35 existing lakes have been modeled by GlabTop2: 5 of the large lakes, 2 of the medium lakes and 2 of the small lakes. Lowering the threshold from 10,000 m^2 to i.e. 3600 (minimum area) would have permitted to model 6 more existing lakes (3 medium and 3 small) but in the meantime, more false positive would have been produced, increasing the uncertainty of the results.

The modeled overdeepenings are mainly larger than the real lakes, this has not to be considered as an error because the overdeepening containing the lake could be entirely but also partially filled with water.

Considering the modeled overdeepenings (tab. 6.1), 9 of them (56%) correspond to real lakes. Analysing the remaining 7 (false positive) by orthophotos interpretation it was found that 2 of them are clearly artifacts (ID 13 and 14) because they don’t correspond to area in counter slope but they are located on leaning bedrock. The other 5 could be real but they are filled by sediment or dead ice instead of water. In one case some water ponds are still forming.

		Modeled values (GlabTop2)				Reality (orthophotos)	
ID	Glacier	Area (m^2)	Max depth (m)	Mean depth (m)	Volume (10^6 m^3)	Max area measured (1990s-2012)	Morphological Observations and notes
1	Rutor	115,200	33	16	1,79	52,500	See Figure 7.5a
2	Rutor	36,000	19	12	0,42	-	Sediments
3	Lavassey	28,800	11	5	0,14	18,100	See figure 7.5b
4	Lys	21,600	8	3	0,07	10,400	
5	Rutor	21,600	6	4	0,08	-	Sediments
6	Gran Neyron West	18,000	24	16	0,29	11,400	See Figure 7.5c
7	Lac Gelè	18000	39	26	0,47	5200	
8	Tsa de Tsan	14,400	8	5	0,08	6700	See Figure 7.5d
9	Punta Laurier North	14,400	19	9	0,13	-	Sediments
10	Soches Tsanteleina	14,400	16	9	0,13	3000	
11	Lys	14400	11	6	0,09	10,200	
12	Lys	10,800	9	5	0,06	3100	
13	Traversiere North	10,800	17	8	0,09	-	Bedrock
14	Monciair	10,800	8	5	0,05	-	Bedrock
15	Mont Gelé	10,800	11	6	0,07	-	Sediments and/or dead ice Figure 6.6a
16	Invergnan	10,800	13	9	0,10	-	Dead ice and water ponds Figure 6.6b

Table 6.1 - Main morphological parameters of modeled overdeepenings compared with the real morphologies.

6.4.3 Backward and local validation

Modeled bedrock was compared with real bedrock topography (2008 LIDAR) in the areas where overdeepenings are assessed but no lakes had formed (fig. 6.6). In the two reported examples it is clear that the profile extracted from the LIDAR represent the elevation of the debris and/or dead ice occupying the proglacial area. There is correspondence between measured and modeled profile up to the step but beyond that they diverge. It is possible that the real bedrock presents an overdeepening (as modeled) but it is not visible both from the orthophotos and the LIDAR because it is filled with debris and/or dead ice.

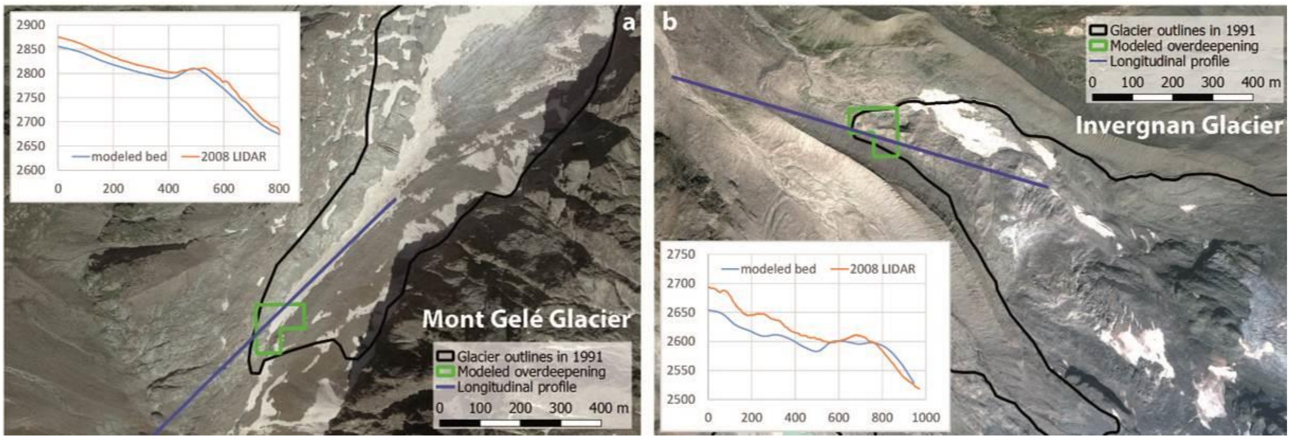


Figure 6.6 - Comparison between modeled bedrock and real surface (2008 LIDAR) for two cases where an overdeepening has been modeled but no real lake exist. (Imagery: Italian National Geoportal. 2006-07 orthophotos).

6.4.4 Forward and local validation

Measured (GPR) and modelled bedrock were compared along points and profiles for the Rutor, Gran Etret and Indren glaciers.

Considering Gran Etret Glacier and Indren Glacier, measured and modeled bedrock elevation were compared along two cross-sectional profiles and one longitudinal profile for both glaciers (fig. 6.7).

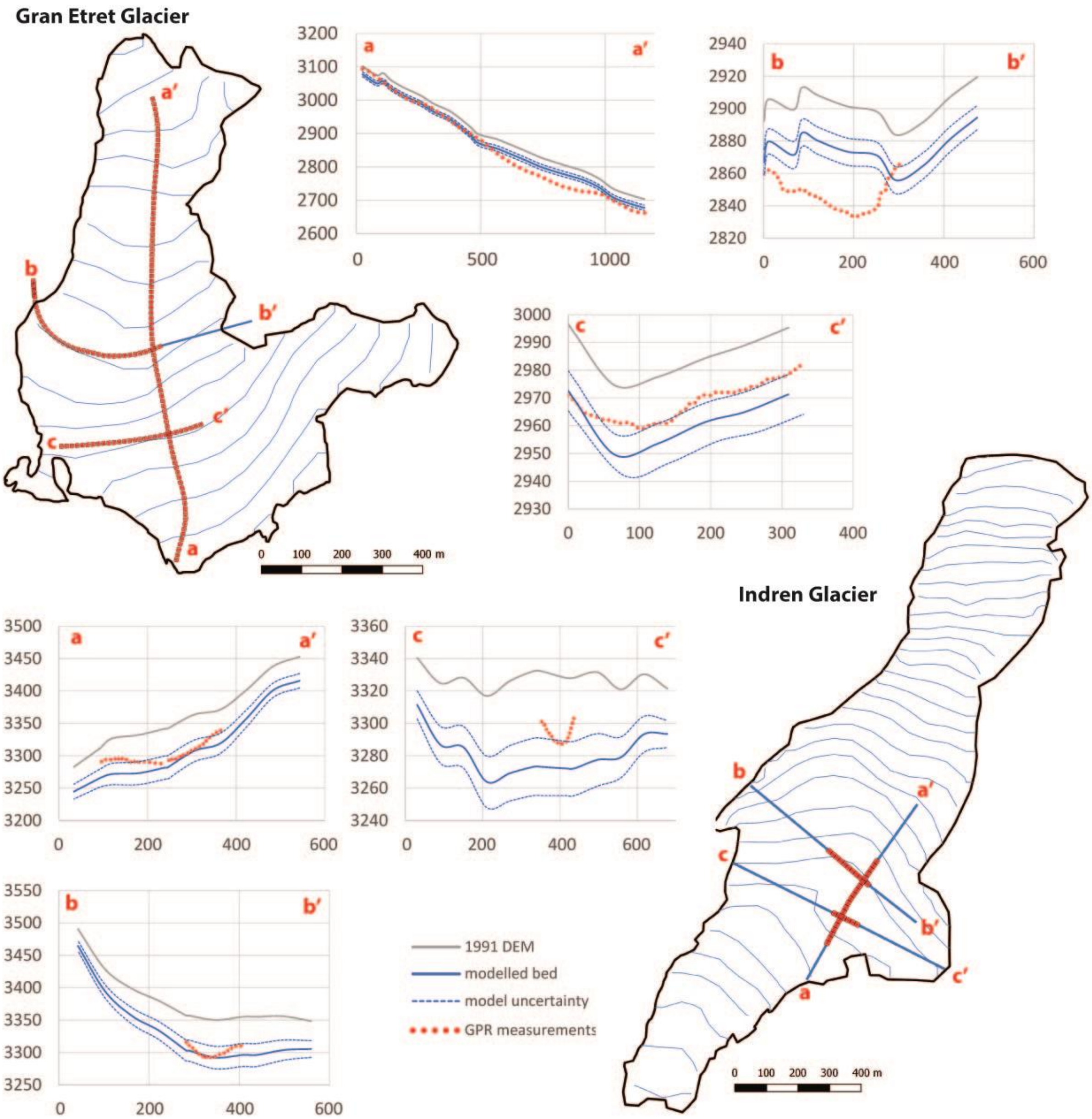


Figure 6.7 - Maps of the modeled bedrock elevation at Gran Etret (top left) and Indren (bottom right) glaciers. The plots show the cross-sectional and longitudinal profiles modeled with GlabTop2, the GPR measurements and the model uncertainity ranging from -30% to +30%.

In the case of Gran Etret Glacier (upper part of fig. 6.7), there is a quite good agreement between measured and modeled bedrock in the highest part of the glacier as shown for the upper part of the profile (a) and for profile (c) and the deviations between measurements and model results mostly remain within the model uncertainty of ±30%. The geometry of the cross sections is well captured for profile (c). On the contrary, the elevation of the central part of the glacier is underestimated by the model (profile a and b) and not within the uncertainty range. Profile (b) shows a large difference between measured and modeled elevation values, the latter underestimating the ice thickness. Considering the geometry of the cross section, the profile seems similar but the different resolution of the model outputs and GPR data and the short track prevent a good comparison.

At Indren Glacier (lower part of fig. 6.7), measurements and model outputs correspond quite well along profile (a) and (b) remaining within the model uncertainty range. Profile (c) shows a proximity between measured and modeled elevation values near the uncertainty range. It seems that the model does not capture the small U-shaped geometry measured by the GPR, the divergence could be due to the low spatial resolution of the model outputs.

The radargrams corresponding to profiles a, b and c of the Indren Glacier are given in the following figures 6.8 and 6.9.

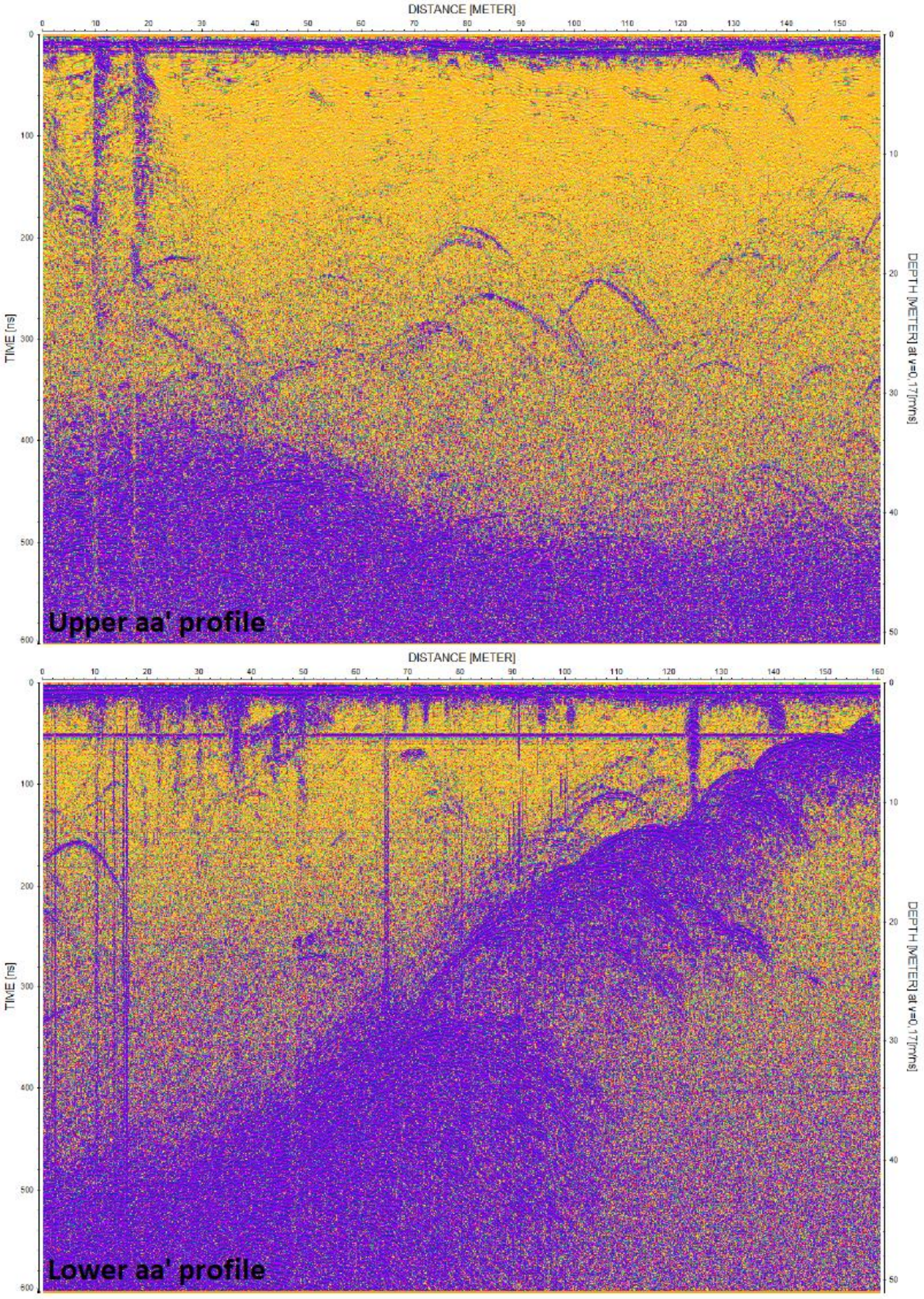


Figure 6.8 – Radargrams of the corresponding transversal aa’ profile at Indren Glacier.

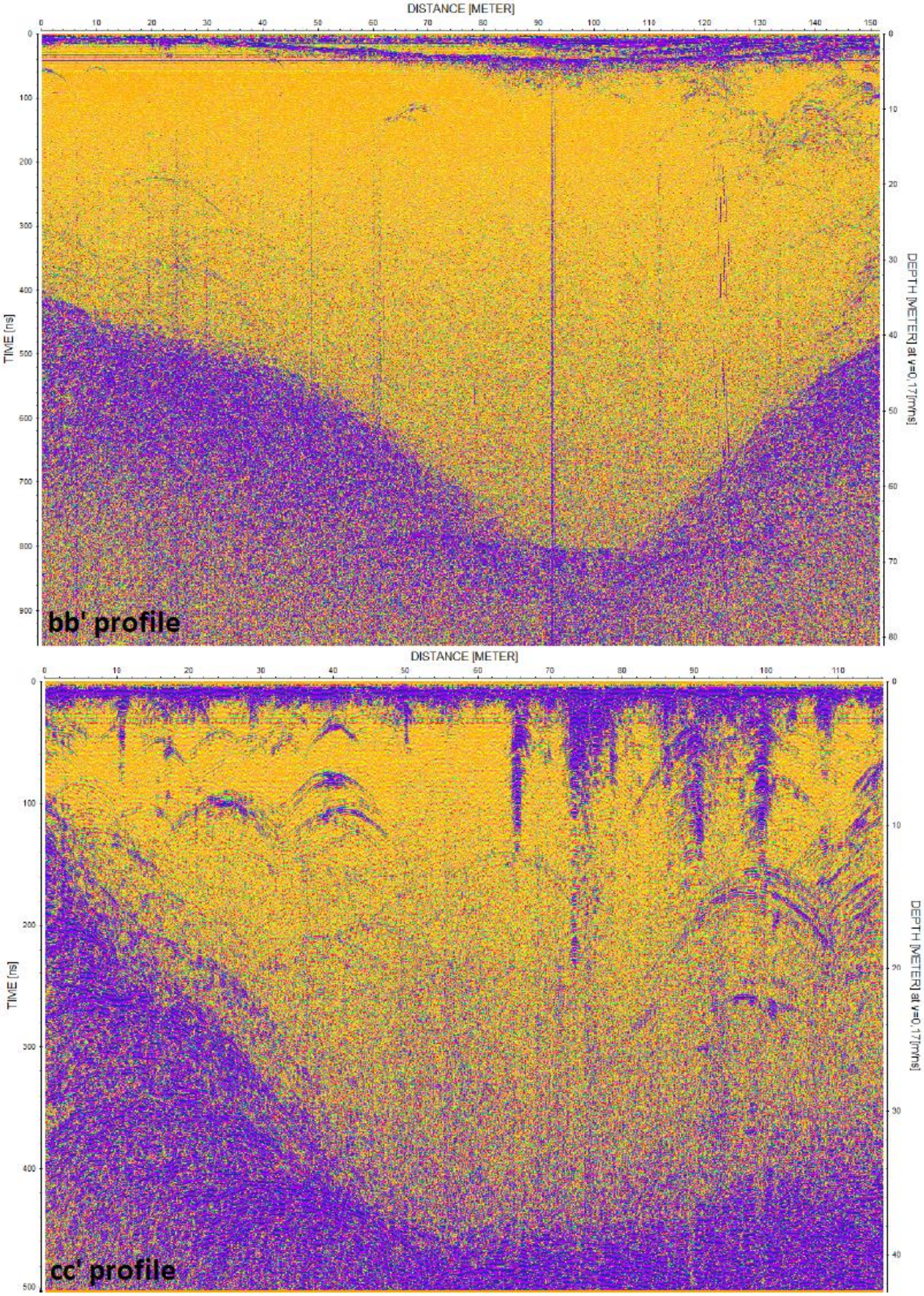
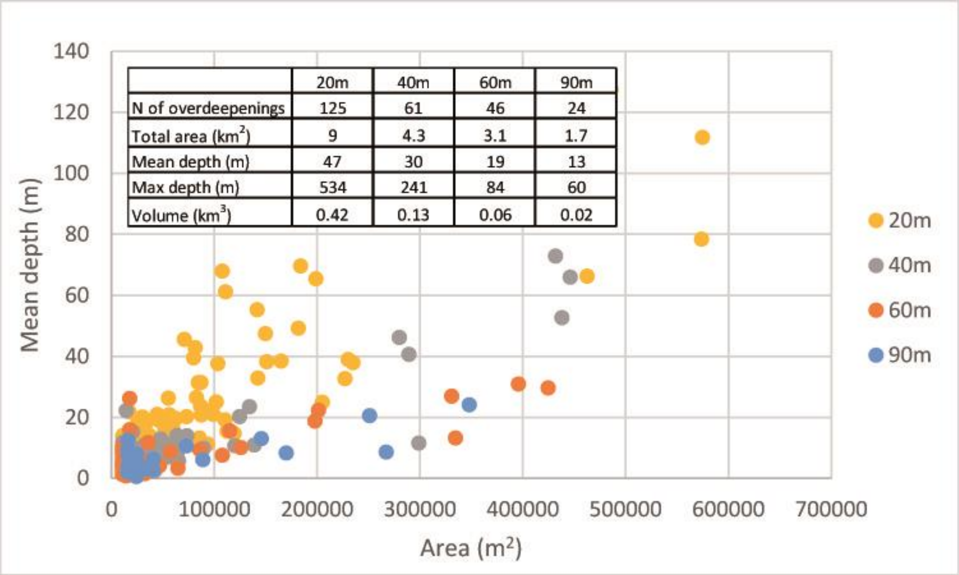


Figure 6.9 - Radargrams of the corresponding longitudinal bb' and cc' profiles at Indren Glacier.

6.4.5 Sensitivity test

Here the results related to changes in the spatial resolution of the input data are presented, different runs of GlabTop2 were performed varying the pixel size of the input data from a high to a low spatial resolution: 20 m, 40 m, 60 m and 90 m. Results focus on the main parameters of the modeled overdeepenings as shown in figure 6.10.



	20m	40m	60m	90m
N of overdeepenings	125	61	46	24
Total area (km^2)	9	4.3	3.1	1.7
Mean depth (m)	47	30	19	13
Max depth (m)	534	241	84	60
Volume (km^3)	0.42	0.13	0.06	0.02

Figure 6.10 - Scatter plot of mean depth of modeled overdeepenings versus their area as modeled for the 20 m, 40 m, 60 m and 90 m runs. The table (top left) reports the main morphological parameters of the overdeepenings for the four runs.

It is clear that a change in the size of the pixel implies a change in the values of the ice thickness and consequently in the number of the overdeeepenings. The number of possible future lakes (surface area > 10,000 m^2) in the study area, and consequently the total area and the total volume, varies considerably with respect to the pixel size of the input data from a minimum of 24 overdeepenings for the 90 m run to a maximum of 125 overdeepenings for the 20 m run. Focusing on figure 6.10, it can be noticed that the majority of the overdeeepenings modeled with the 40, 60 and 90 m spatial resolution have an area lower than 100,000 m^2 and a depth lower than 20 m. Results of the 20 m run show an increase in the number, area and depth of the overdeepenings. The 20 m run has the positive advantage to be more defined when the geometry of the profiles is analysed. For example, profile b of the Gran Etret Glacier and profile c of the Indren Glacier modeled with the 20 m run are more in agreement (only looking at the shape) with the GPR data than the one modeled with the 60 m run (figure 6.11).

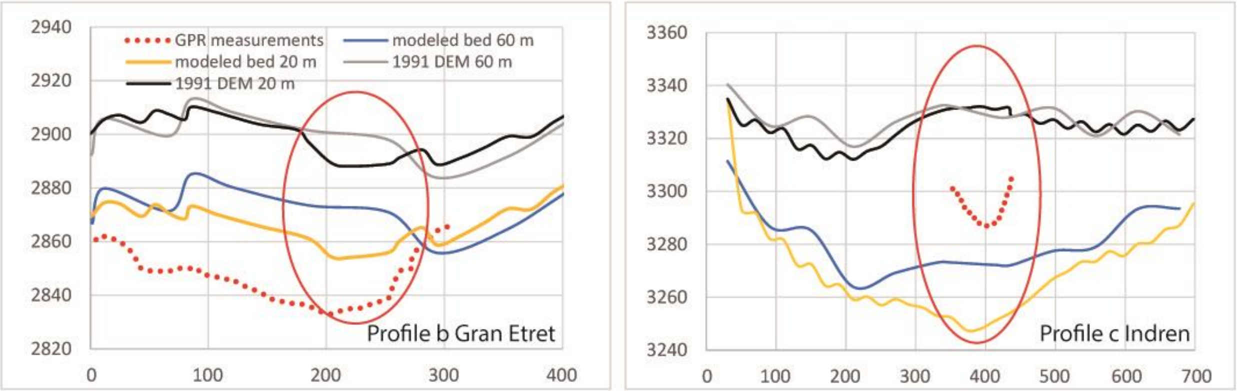


Figure 6.11 - Comparison between 60 m and 20 m model outputs and GPR measurements along cross-section at the Gran Etret and Indren galciers.

The modeled overdeepenings were compared with existing lakes for the four runs, the results are shown in figure 6.12. It can be noticed that the 20 m run has the highest number of modeled lakes but it is also the one with the highest number of false positive. These are mainly located at glacier margin where the calculation of glacier surface slope could be uncertain and consequently produce artifacts. Modeled lakes, as well as false positive, decrease with the decrease of the spatial resolution. Looking at the large modeled lakes it can be noticed that all the four runs modeled about more than the 50% of the large lakes.

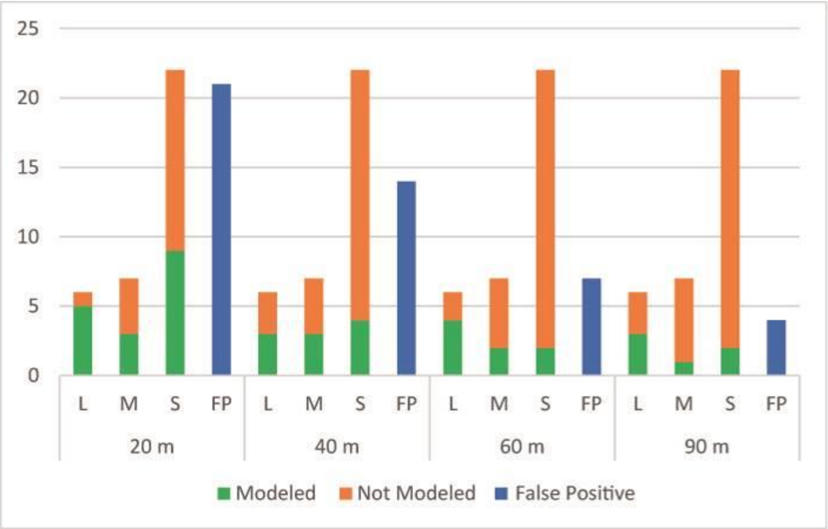


Figure 6.12 - Model performances for the four different runs (20 m, 40 m, 60 m and 90 m). The plot reports for each run the number of modeled (green, M) and not modeled real lakes (red, NM) differentiating among large (L), medium (M) and small (S) existing lakes and the overdeepenings that not correspond to real lakes (blue, false positive, FP).

7 GENERAL DISCUSSION

7.1 PAST EVIDENCE

7.1.1 Examples of lake formation and evolution: the importance of integrating different data sources

In order to demonstrate the usefulness of integrating historical maps, orthophotos and reports of the glaciological surveys, two examples regarding the formation and successive evolution of glacier lakes are presented.

The first example (fig. 7.1) concerns the Tzere Glacier located in the Ayas Valley (Monte Rosa group, Pennine Alps, Aosta Valley). In fig. 7.1a the glacier reached the rock step at about 2860 m a.s.l.; in 1969 (fig. 7.1b) the glacier front retreated, leaving an overdeepened area occupied by a newly formed lake. In 1976, the glaciological survey reported: "Below the western slopes of the Rocca di Verra it has formed a periglacial lake (2900 m a.s.l.) of about 250 x 80 m". The lake increased in size and survived until 2012 (fig. 7.1c).

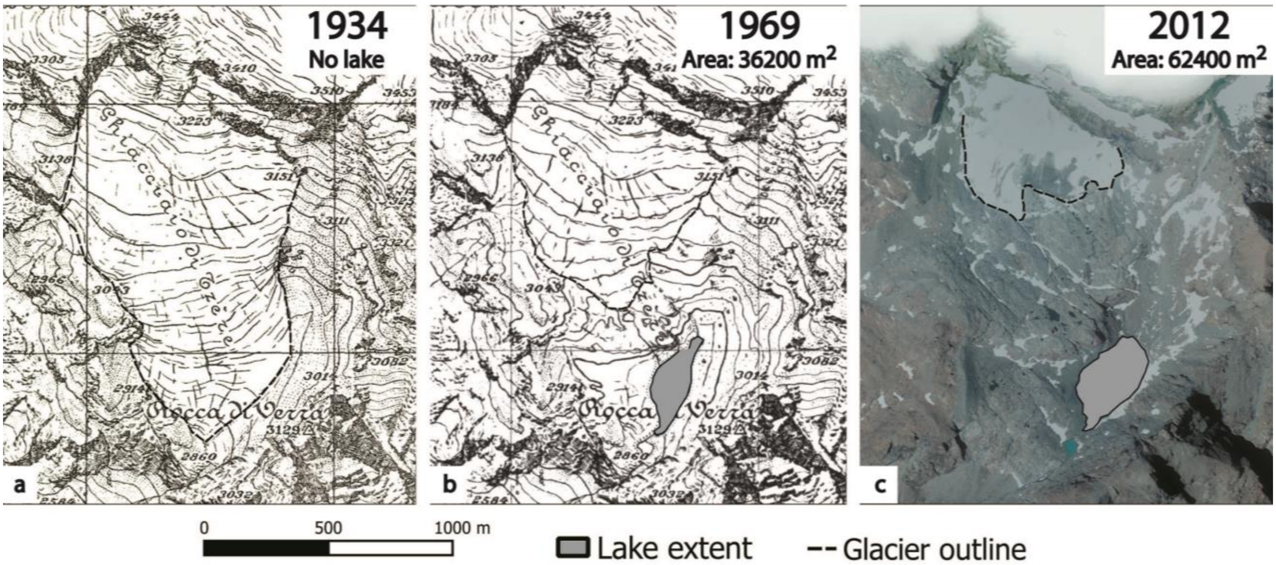


Figure 7.1 - Tzere Glacier (Monte Rosa Group, Pennine Alps) on two successive editions of the IGMI sheet 29 I SO, Saint Jacques (1934 and 1969) and in the 2012 orthophoto (Imagery: Italian National Geoportal).

The second example is represented by the Ban Glacier in the Formazza Valley (Monte Leone-Blinnenhorn chain, Lepontine Alps, Piemonte). In 1974, the operator of the CGI reported: "The glacier has not been surveyed since 1971. The glacier front "plunged" into a little lake dammed by a huge moraine". The successive evolution of the lake could be reconstructed by the orthophotos set (fig. 7.2), where the progressive retreat of the glacier and the consequent enlargement of the lake is clearly recognizable.

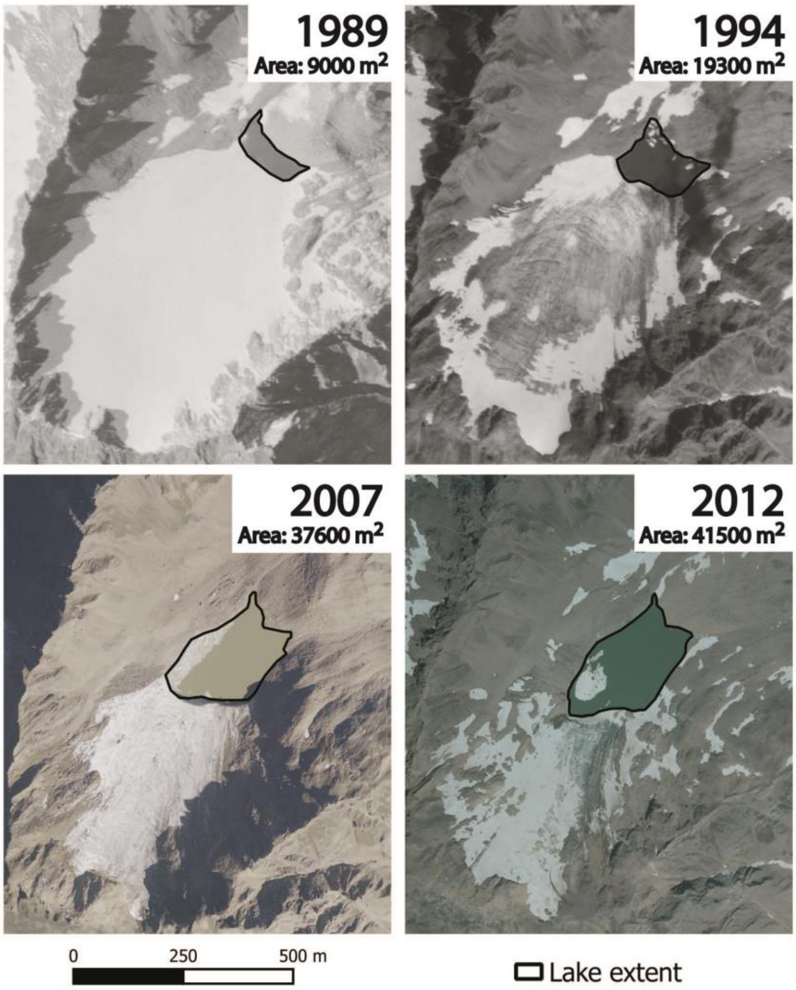


Figure 7.2 - Formation and evolution of a proglacial lake at Ban Glacier (Monte Leone-Blinnenhorn chain, Lepontine Alps) between 1989 and 2012 (Imagery: Italian National Geoportal).

7.1.2 Glacier lake inventories by topographic maps and orthophotos: advantages and limitations

The analyses and interpretation of topographic maps and aerial orthophotos allowed to identify, map and measure glacier lakes within different time steps. The integration of different data sources has been necessary in order to cover a wide time period, as it has been required in this study of the post-LIA modification of glaciated mountains of the Western Italian Alps.

Before the onset of aerial photogrammetry techniques, historical maps represent the only available data for cartographic purposes. The present study demonstrates the usefulness of historical maps: 43 and 66 lakes were identified and mapped in the 1930s and in the 1970s respectively, despite the map nominal scale being 1:25,000. Moreover, for some selected cases it has been possible to reconstruct the condition of formation and the evolutionary stages of glacier lakes (e.g.: Tzere Glacier).

However, it is important taking into account qualitative and quantitative errors that can result from historical maps used as data sources. A historical map is a product of successive activities: direct topographic measurements, maps production and successive cartographic updates. For all these reasons it is difficult to know if the map is the real representation of the study area in a certain time. Consequently, from a qualitative point of view, the real presence or absence of lakes may not always be fully certain, considering also their ephemeral nature. Furthermore, the difficulty in map symbols interpretation, can sometimes make the existence of lake doubtful.

Concerning quantitative errors, the total areal error is calculated as the percentage of all the buffer areas with respect to the total lake coverage (see Chapter 5.3).

Digitizing lake outlines using historical maps as a base layer leads to a ±6-7% total areal error in the 1930s and 1970s. This must be taken into account once doing comparison of lakes total area through time.

In contrast to this, orthophotos due to their image GSD (Ground Sample Distance) minor than 1 m, allowed an accurate identification and digitalization of lakes. For example, during 2006-2007 the availability of high resolution images all over the study area allowed detailed dimensional characterization also of small lakes (<1000 m^2) that represent 30% of the population. The total areal error in this case is less than ±1%.

The main practical problems experienced in orthophoto analysis are: the digitalization of lakes that appear partially or totally frozen, despite photos were mainly acquired during summer; shadowed areas due to the acquisition flight time and relative elevation; the discrimination between lakes and flooded areas.

7.1.3 Main types of glacier lakes and processes

From the analysis of the obtained results related to the past evidence important considerations can be proposed concerning the main types of glacier lakes detected in the study area and of the morphodynamic processes recognized in the considered time period. Figure 7.3 summarizes it.

Three main types of glacier lakes have been detected:

1) the most common type are **lakes dammed by bedrock** (fig. 7.3a). They represent the majority of the detected lakes in the study area (about the 80%), they fill glacier bed depression also called overdeepenings modeled by the erosive action of the glaciers. Their area can be very large exceeding 50,000 m^2. Their dimensions are quite stable and the water level depends mainly by the incoming water (ice and snow melting

and precipitations). With their dam being constituted by generally stable bedrock, potential outburst can primarily be caused by the impact of ice, snow or rock avalanches into the water and the generation of a wave.
2) the second most common type of l**akes** are those **dammed by moraines** (fig. 7.3b). They represent about 20% of the population. In the majority of the cases lakes are dammed by the huge moraines formed during the LIA like the Locce Lake at the Locce North Glacier (Monte Rosa massif, Anzasca Valley, Pennine Alps) or the Lago Blu (Blue Lake) at the Verra Grande Glacier (Monte Rosa massif, Ayas Valley, Pennine Alps). There are also interesting examples of lakes dammed by the smaller moraines formed during the two glacier advances which occurred during the 1920s and 1970s. In figure 7.3b the moraine-dammed lake at the Gran Neyron Glacier (Gran Paradiso chain, Graian Alps) is shown. The moraine has formed during the 1970s glacier advance. These relatively small and young morainic dams are less stable than LIA moraine dams..Moraine-dammed lakes can be more dangerous than bedrock dammed-lakes because in addition to being hit by ice/rock falls they can be subjected to moraine breaching (Westoby et al., 2014). The causes can be different, for example: erosion, ice core melting, water seepage.
3) the third type of lakes that has to be mentioned are the **supraglacial lakes** (fig. 7.3c). They constitute less than the 2% of the lake population. The most famous supraglacial lake in the study area is the Ephemeral Lake at the Belvedere Glacier (Monte Rosa massif, Anzasca Valley, Pennine Alps, see chapter 4). They mainly form on the surface of debris-covered glacier like Miage and Belvedere but there are also examples on debris-free glacier like the one on the Moncorvè Glacier (Gran Paradiso chain, Graian Alps). Some of them can form also on dead ice detached from the glacier like the supraglacial lakes and ponds at the Lys Glacier (Monte Rosa massif, Lys Valley, Pennine Alps). Supraglacial lakes in the study area are quite small and ephemeral, their life cycle can last only one season because their existence is strongly dependent on the glacier movement. The associated danger is strongly connected to their dimension, for example the Ephemeral Lake named before was of big concern (see chapter 4).

It was possible to identify different processes which occurred in the study area by the analysis of the collected data. In particular, the dynamics responsible of the **appearance/disappearance** and **increase/decrease** of glacier lakes are described.
The proglacial area of the Rutor Glacier offers perfect examples of most of the identified processes (fig. 7.3d). Lakes appeared in the area because of the glacier retreat, they occupy depressed basins in the debris or bedrock

overdeepenings left by the glacier. The progressively shrinkage of the glacier front is followed by an increase in the number of new lakes and allowed the areal increase of the existing ones. The disappearance of an existing lake can also be noted and can be attributed to infilling processes by glacier fine debris. Finally, an interesting process is the one which occurred at the Miage Lake (Mont Blanc massif, Veny Valley, Graian Alps). The lake water level progressively lowered at the beginning of the 2000s due to englacial drainage. The consequence is the fractioning of the main lake body into four smallest lakes (fig. 7.3c).

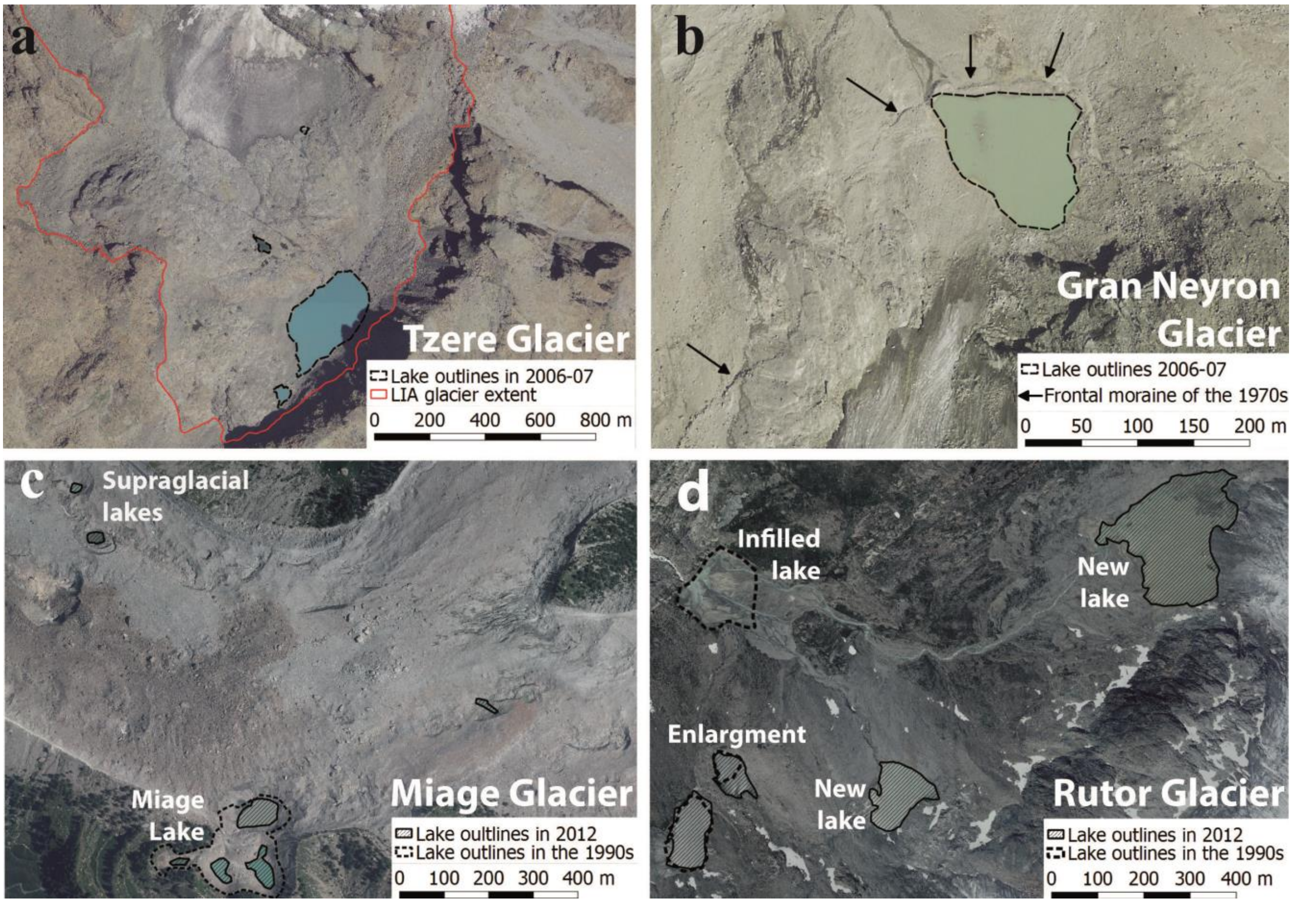


Figure 7.3 - Main type of glacier lakes and processes: a) bedrock-dammed lakes (Orthophotos 2006-07); b) moraine-dammed lakes (Orthophotos 2006-07); c) supraglacial lakes and fractioning of the Miage Lake after the 1990s (Orthophotos 2012); d) processes of infilling, enlargement and formation of new lakes (Orthophotos 2012). (Imagery: Italian National Geoportal).

7.1.4 Consideration on changes in the number of glacier lakes from the 1930s to 2012

The total amount of mapped lakes (lake population) during the period 1930s-2012 is 254, but they have never been surveyed all in the same time step.

An analysis on the causes of the changes in the total amount of lakes in each time step was performed (fig. 7.4), to understand what happened to glacier lakes during the considered period.

All the areas where lakes have been detected were observed on the maps and on the orthophotos. For each time step the observations were classified in 7 different categories. The first four classes are directly related to the lakes, which can be distinguished as:

1) “survived” lakes with respect to previous inventories (dark blue bar);

2) new lakes which appeared for the first time (light blue bar);

3) detected but not mapped lakes which can be identified on the orthophotos but can’t be precisely mapped because partially covered by snow or ice (turquoise bar);

4) disappeared lakes with respect to the previous inventories (green bar).

Lakes not classified in previous classes are those which had not yet appeared within the considered time step. By a retrospective analysis their supposed location was observed in order to understand how were these areas before the formation of the lakes. Related areas are classified in 2 more categories:

5) areas occupied by the glacier (violet dotted line), it means that the lake formed when the glacier freed the area;

6) glacier-free areas (bedrock or debris) (grey dotted line), it signifies that before the lake formation the area was characterized by free bedrock or by debris with no evidence of the presence of water.

A further category has been introduced, namely:

7) “uncertainty” (identified by the orange line), defined as the number of lakes for which it was not possible to understand if they are present or not within the considered time step. The uncertainty is due to lack of data (this is the case only of the 1970s IGMI map), snow cover (related to the acquisition flight date) or shadowed areas (related to the acquisition flight time and relative elevation).

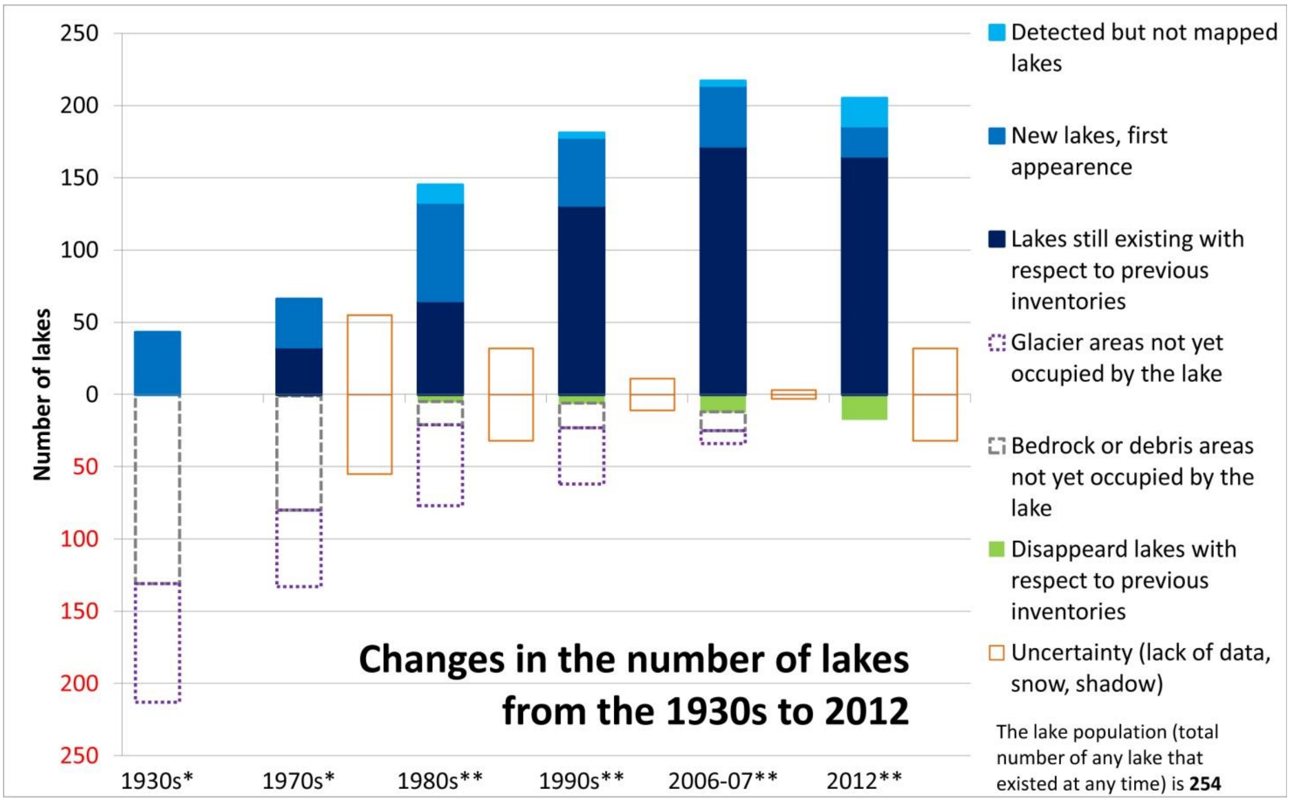


Figure 7.4 - Changes in the number of glacier lakes from the 1930s to 2012. Data were derived from * historical maps and ** orthophotos. The lower part of the y-axis (red numbers) represents upcoming and/or disappeared lakes.

Starting from the **1930s** only 17% of the total amount of lakes was present in that period.

Considering the **1970s** inventory, only 33 of the 43 detected lakes within the 1930s time step have been identified. Only for one of them the real disappearance on the IGMI map of the 1970s could be verified. Considering the other 9 lakes, a lack of data prevented further interpretation: in fact, none updated version of the IGMI map for the 1970s is available for the Marittime Alps, the Gran Paradiso group and the Lepontine Alps. Since no data are available for the 22% of the total amount of lakes (represented with the orange line), they could have survived, disappeared or appeared with respect to the previous inventory. However, an increase in the number of lakes can be noticed: 33 new lakes formed, 13 of them appeared after a glacier retreat stage happened between the 1930s and the 1970s.

In the **1980s** time step, the number of lakes doubled with respect to the previous inventory: 65 new lakes appeared. Starting from the 1980s the third category of lakes was introduced, it refers to the lakes that can be identified on the orthophotos but can’t be precisely mapped, because partially covered by snow or ice. In the 1980s, they represent the 5% (12 lakes) of the total population.

It is interesting to note the numerical difference between the 1970s and the 1980s in the “areas occupied by the glacier” bar: this means that two lakes existed in the 1970s but disappeared in the 1980s. In particular, two proglacial lakes appeared in the 1970s at the front of the Lys Glacier, as indicated by both historical maps and reports of the glaciological surveys (CGI, 1971-1975). In the 1980s these two lakes disappeared, because their location is occupied by the re-advancing glacier front.

Because of the presence of snow, 13% of the lakes were not detectable.

The increase in the number of lakes continues in the **1990s**: 131 lakes survived and 47 new lakes formed. Only few lakes (6) disappeared, probably because of infilling processes; also there are only few not detectable lakes (11).

In **2006-07** the maximum number of detected lakes was reached (217 lakes, which include mapped lakes and detected but not mapped lakes). The majority of new lakes (62%) were located in areas previously occupied by glaciers, their appearance is consequently due to glacier retreat. 12 lakes disappeared in 2006-07, the observation of the orthophotos allowed to understand the causes: they were filled in by sediment.

The 2006-07 orthophotos are those with the best quality among all data sources: only in 3 cases it could not be asserted whether the lake was present or not because of snow cover. The 99% of the investigated areas is clearly visible. This fact makes this inventory the most accurate among the six inventories.

Concerning the **2012** time step there is a slight decrease in the total number of detected lakes (205 lakes against 217 lakes in 2006-07). Some hypothesis about the causes can be proposed. Certainly the number of disappeared lakes increased with respect to the previous inventories: 17 lakes disappeared, mainly because of infilling processes, and there are also 6 cases of ephemeral supraglacial lakes, formed on the surface of debris-covered glaciers in 2006-07 (Miage and Belvedere glaciers) and emptied in 2012. It is also clear that in the first half of July 2012, when the aerial photographs were taken, the snow cover was considerably extended on the investigated areas (13%); this prevented to understand whether some lakes (32) survived or disappeared.

7.2 FUTURE SCENARIOS

7.2.1 Future landscape evolution in Aosta Valley Region

Compared to the total glacier volumes (7.3 km^3), the calculated possible future overdeepenings volume (0.06 km^3) is about 0.8%. Considering similar studies, it has to be noticed that the value is significantly less than the corresponding value calculated for the Swiss Alps (3%, Linsbauer et al., 2012) and the Himalaya-Karakoram (3-4%, Linsbauer et al., 2016). On the contrary, similar values are founded for the Peruvian Andes (0.5-1%, Colonia et al., 2017), where, as in the present study area, about 80% of the glaciers are smaller than 1 km^2.

If glaciers and lakes area are compared, it is evident that from the end of the LIA until 1991 the lakes (1.1 km^2) occupied 0.6% of the area previously occupied by the glaciers (179 km^2). On the other side, the total area of modeled overdeepenings (3.1 km^2) is 1.9% with respect to the area of the remaining glaciers in 1991 (163 km^2). The differences in the values could be attributed to the fact that not all the past overdeepenigs had given birth to a lake and the same can happen in the future, especially considering the increase in the amount of available morainic debris becoming exposed on slopes which can fill future overdeepenings. The presence of breaches or gorges in the dam could also prevent the accumulation of water, as suggested by Colonia et al. (2017).

Flat areas are the more suitable for giving birth to new lakes. Glaciers of the Aosta Valley, as the Peruvian glaciers, lost their flat tongues in the recent past. There are still extended flat areas in the remaining glaciers located in the accumulation zones of some of the largest glacier (Tribolazione, Rutor, Pré de Bar, Triolet, Grandes Murailles). The majority of larger and deeper possible future lakes are modeled underneath these areas.

More than a half of the potential overdeepenings are located in the lowest areas of the glaciers and are the smallest and shallowest of the population. The areas where these overdeepenings are located will probably be freed by the glaciers in the coming years, considering the rate of the present glacier retreat. On the other hand, the largest and deepest overdeepenings are located in the accumulation areas of the widest and thickest glaciers of the region, located in the main mountain massifs and at high elevations. Taking into account the future scenarios related to these few largest glaciers which will probably be able to resist some coming decades (Zemp et al., 2006), the related overdeepenings will not appear very soon but nevertheless probably before the end of the century.

7.2.2 Suitability of GlabTop2 to anticipate the formation of glacier lakes and to model overdeepenings in the study area

The comparison between modeled overdeepenings and existing lakes shows good performances of GlabTop2, especially for the lakes with area larger than 10,000 m^2 (fig. 7.5 a, b, c). The model is also able to predict the location of some of the medium size lakes (area between 5000 and 10,000 m^2) as shown in figure 7.5d.

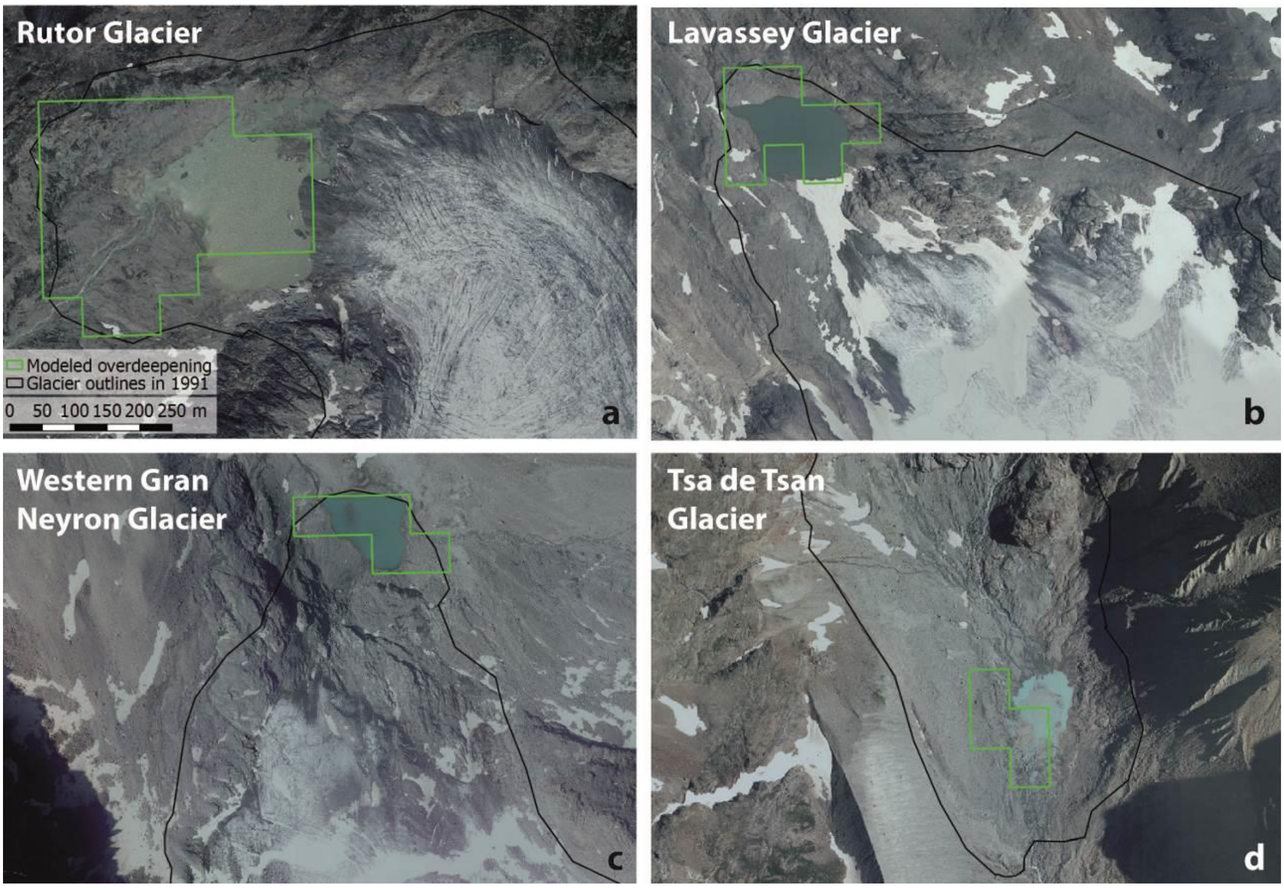


Figure 7.5 - Correspondence between the location of modeled overdeepenings and existing large (a, b, c) and medium (d) lakes in the study area (Imagery: Italian National Geoportal. 2006-07 orthophotos).

The location of the modeled overdeepening has been analysed considering morphological criteria described by Frey et al., 2010 (fig. 7.6a) in order to understand if they could correspond to real bed-overdeepened morphologies. The reported examples (fig. 7.6 b, c) show a good correspondence with the three criteria: 1) distinct break in slope; 2) reduction in glacier width; 3) heavily crevassed glacier part below a crevasse-free part. The location of modeled overdeepenings also corresponds with areas having surface slopes < 5°, that is a preliminary good criteria for pre-selecting sites with possible overdeepenings as suggested by Frey et al. (2010).

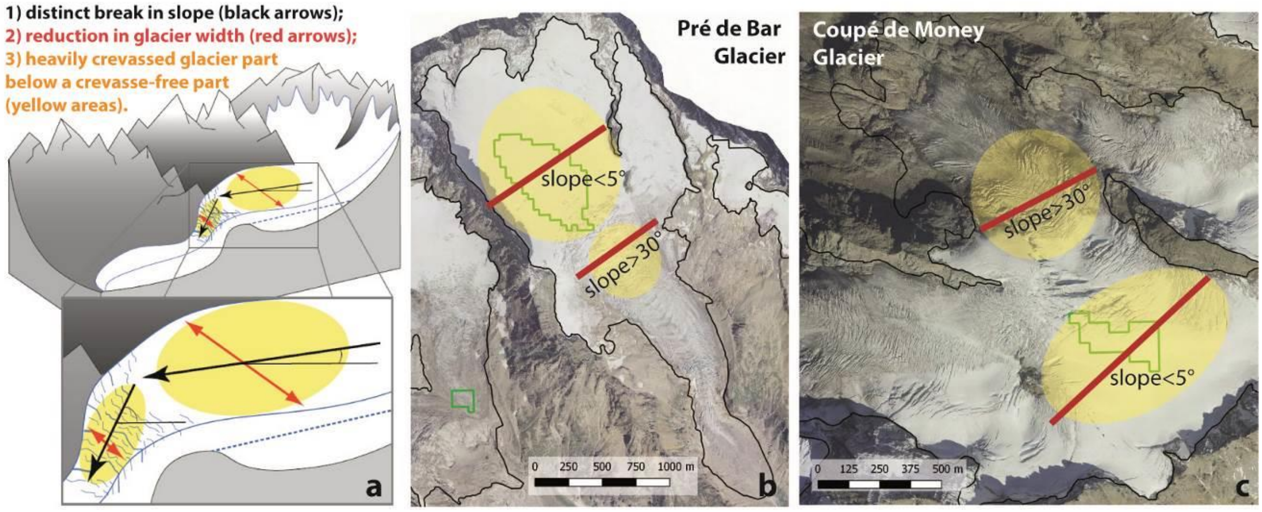


Figure 7.6 - Morphological criteria (a, from Frey et al., 2010) that indicate the potential existence of glacier-bed overdeepenings for two cases in the study area: Pré de Bar Glacier (b, Mont Blanc massif) and Coupé de Money Glacier (c, Gran Paradiso chain). (Imagery: Italian National Geoportal. 2006-07 orthophotos).

The location and the areal size of the modeled overdeepenings is quite robust. The other parameters like the depth and consequently the volume are less certain.

There are still some problems in modeling ice thickness and consequently overdeepenings for glaciers with shape and dynamics similar to ice cap, as already shown by Farinotti et al. (2017) and demonstrated with the case of Rutor Glacier below. The results for this type of glaciers have to be interpreted keeping in mind that model outputs can overestimate the real values of ice thickness, especially in the most flat and wide area of the glacier. In fact, analyzing the differences between the elevation of the bedrock measured by the GPR and the one modeled by GlabTop2 at Rutor Glacier (fig. 7.7), it was found that the model underestimated the elevation to a maximum value of 47 m and overestimated it to 174 m. The highest differences are given by those areas where the model assesses potential overdeepenings, which correspond to the flattest area of the glacier. Along the rest of the measured points the differences are lower and in between about ±40 m. The Rutor Glacier cannot be defined as a proper valley or mountain glacier, and probably its dynamic is highly influenced by the structural conditions of the bedrock: these could be the reasons of such divergence between measured and modeled values. In addition, the upper flat (firn) zone is close to a "firn divide" where surface slope becomes zero and the basic assumption of the GlabTop approach (constant basal shear stress) breaks down. The lower flat zone today part of the ablation area may be a diffluence site but this does not explain the extreme differences. Analysing measured ice thicknesses in correspondence with the modeled overdeepenings it can be noticed that the values of the maximum thickness are: for the overdeepening in the upper flat zone 52 m and for the one in the lower flat zone 78 meters. Finally, analyzing the GPR path in correspondence of the modeled overdeepning it seems that no real overdeepened morphologies exist.

Errors during the acquisition (anthenna, frequency, maximum depth) and processing of the GPR data have also to be taken into account.

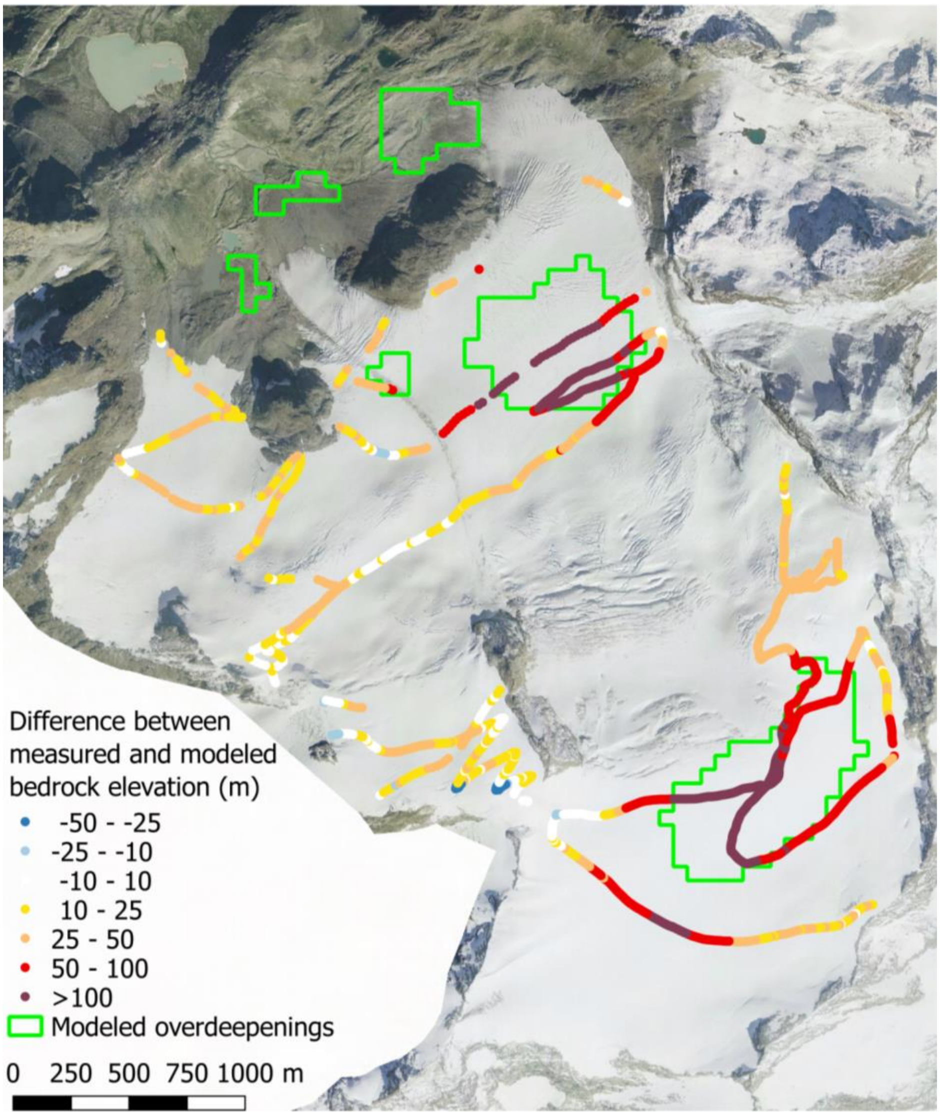


Figure 7.7 - Difference between measured (GPR) and modeled bedrock elevation (GlabTop2) at Rutor Glacier along GPR path. (Imagery: Italian National Geoportal. 2006-07 orthophotos).

7.2.4 Usefulness of the backward and forward validations

When this PhD project started, the backward approach had been proposed only once by a master thesis (Rüesch, 2013), representing an innovation in the methodologies for validating and evaluating the performances of the model. In particular, the backward approach fills a gap in the research in the meaning that it allows to compare modeled results with the reality (real lakes and recent DEM of the deglaciated areas) and with a good degree of confidence with respect, for example, to the validation with the GPR data which have a larger range of uncertainty because of the data acquisition and interpretation (Colonia et al., 2017).

Moreover, it has to be taken into account that quite long GPR paths are needed for making a reasonable comparison of the measured and modeled bedrock profiles because of the large pixel size of the output raster. Short paths can be used for the validation of the ice thickness at certain points but not to validate the shape of the bedrock and, in the case of the identification of the overdeepenings, their real existence. Moreover, analyzing GPR profiles in 2D is limiting because of the strongly 3-D geometry of the overdeepenings.

For these reasons, if a GPR survey has to be planned, the selection of the glacier has to be based also considering its dimension and the possibility of making enough long paths in both longitudinal and transversal directions.

7.2.3 Effect of the input data on model results

The main differences in the model results depend from the spatial resolution of the DEM in input. The smaller the pixel size is, the higher is the ice thickness and the number of modeled overdeepenings and vice versa for larger pixels. Moreover, as described by Haeberli et al., 2016b, inter-/extrapolation methods also have an influence.

Considering the comparison between measured and modeled bedrock profiles it has to be noticed, as it was described by Paul & Linsbauer (2012), that the variability of the DEM is transferred to the bedrock that is extracted by the subtraction of the ice thickness from the DEM. This explains the better performances, in terms of visual matching, for the high spatial resolution run. Existing lakes were compared with the modeled overdeepenings of the four runs and it was found that the larger one have been well modeled, which confirm the robustness of the model in assessing the location of the overdeepenings and approximately their size.

Based on these findings, it is better to choose a medium pixel size (about 40 or 60 m) in order to avoid a great number of false positive results and the overestimation of the ice thickness, overdeepenings depth and volume but in the same time to be able to model a good number of real lakes, especially the larger ones.

7.3 THE IMPORTANCE OF GLACIER LAKES IN THE WESTERN ITALIAN ALPS: POSSIBLE USES AND POTENTIAL HAZARDS

The present research allows to better understand and demonstrate the significance of glacier lakes in the study region. In fact, existing and potential future lakes in the Western Italian Alps, such as in other regions of the Alps, are of considerable importance for several reasons presented in the following.

In figure 7.8 existing glacier lakes have been classified in different categories with respect to their uses and/or potential hazards. Information for classifying the lakes have been collected during the PhD activities by scientific literature, bulletins of the Italian Glaciological Committee and data stored in the archive of the CGI (books, photos, orthophotos).

Six categories are proposed:

1) no uses and hazards observed, it contains all the lakes for which no evidence of uses and/or hazards are recognized;

2) water supply, it comprehends the lakes used by mountain hamlets and/or huts as water provision identified by the description of the CGI volunteers in the glaciological surveys;

3) hydropower, it includes all the lakes exploited for the production of hydroelectricity recognized by the presence of artificial dams, power plants and pipes;

4) tourism, it contains the lakes that represent a high tourist value as indicated by guidebooks;

5) tourism and hazard, it comprehends all the lakes that present at the same time a tourist value and a hazard potential;

6) hazard, it includes the lakes with associated hazard potential (outburst and consequent flood) as indicated by the related scientific literature.

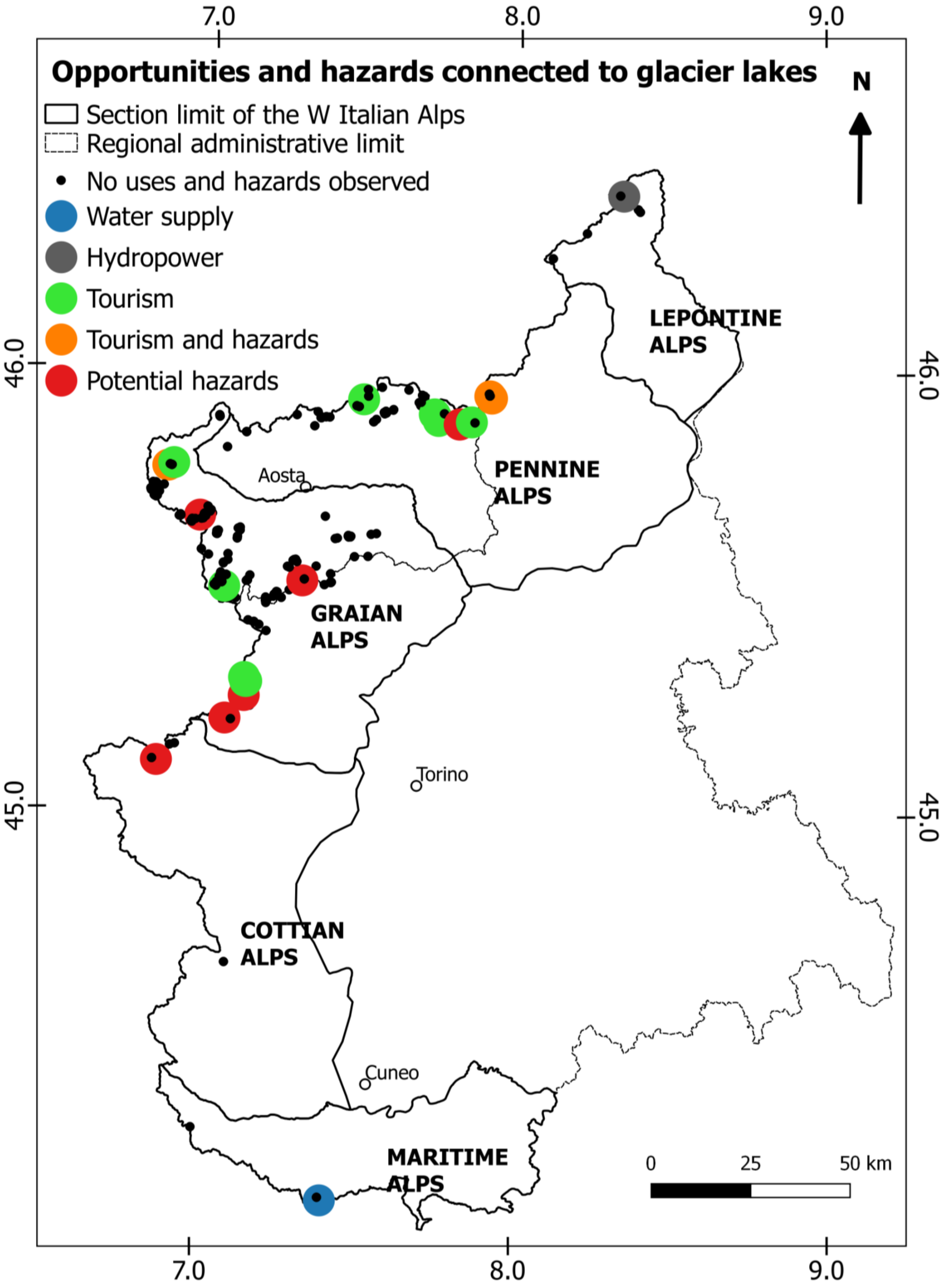


Figure 7.8 - Map of the opportunities and hazards connected to the presence of glacier lakes in the Western Italian Alps.

7.3.1 Opportunities related to glacier lakes

As Haeberli et al. (2016a) underlined, glacier lakes in the Alps represent an opportunity in terms of their use for: water supply, hydropower and tourism. Multiple uses of glacier lakes can be identified also in the Western Italian Alps.

Glacier lakes are, for example, exploited as **water supply** for mountain huts. Reports of the glaciological surveys described, already in the 1930s, the dependence of the Pagarì Hut in the Maritime Alps on the presence of the lake at the Maledia Glacier. Potential future lakes will be located at progressively higher elevations in the main mountain massifs (Monte Rosa, Monte Bianco and Gran Paradiso) where high altitude huts exist and can benefit from this water basin. In fact, lakes are taking the place of vanishing glaciers. The Losa Lake in the Graian Alps has appeared in the 1980s, partially taking the place of the vanished Losa Glacier (fig. 7.9a and 7.9b). The problem is that the replacement is only partial: the calculated total volume of potential future lakes is less than 1% of the volume of existing glaciers.

Existing lakes or alluvial planes located in proglacial areas with favorable conditions were selected in the past for the construction of artificial dams, the stored water has been used for **hydropower production**. A good example in the study area is the Sabbione Lake in the Pennine Alps that has been artificial dammed in the 1950s (fig. 7.9c and 7.9d). The exploitation of future lakes for energy generation has to be taken into account as it has be done in the Swiss Alps for the Trift Glacier (Haeberli et al., 2016a) or for the Glacier de Corbassière (Terrier et al. 2011).

From an economic point of view, glacier lakes have represented also elements of **tourist attraction** in the Alps. In Aosta Valley the most famous example is of course the Miage Lake in the Veny Valley, many tourists visit the beautiful moraine amphitheater and the lake every year (fig. 7.9e). Also the hazardous Ephemeral Lake at the Belvedere Glacier has represented an attraction: during its existence, dedicated signs indicating observation points where installed. The touristic value of glacier lakes has also been supported by the realization of dedicated paths and panels for guided trekking: a recent project was completed in Lanzo Valleys (Graian Alps) across the proglacial area of the Bessanese Glacier (fig. 7.9f). New lakes can be valued by similar projects always keeping in mind the surrounding environment with its fragilities and potential hazards.

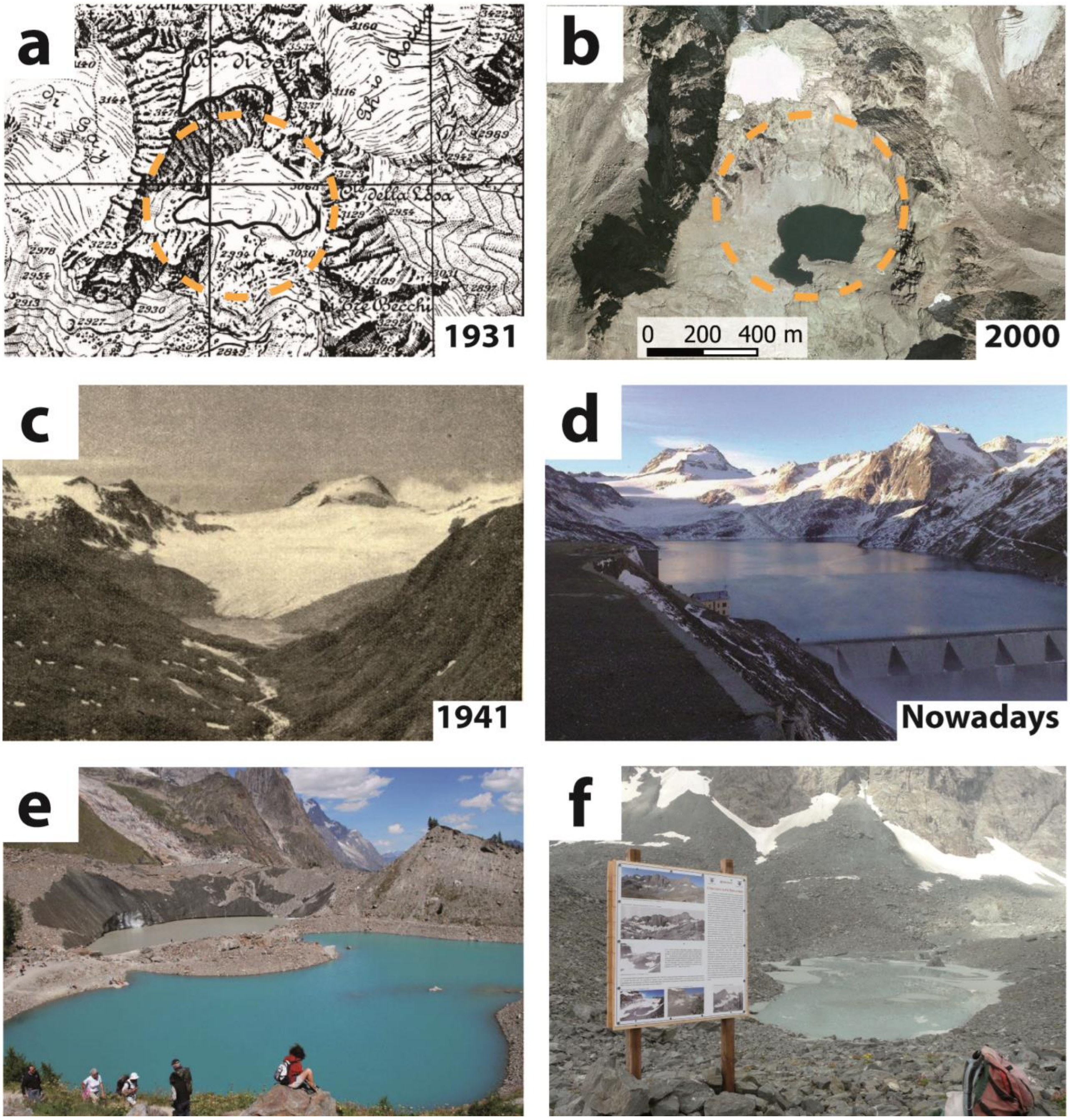


Figure 7.9 - Opportunities related to the presence of glacier lakes: a) Losa Glacier on the IGMI sheets 41 I SO, Gran Paradiso (1931) and 41 I SE Torre del Gran San Pietro (1931) later substituted by b) Losa Lake (2000 orthophotos, Italian National Geoportal); c) proglacial lake at Sabbione Glacier (ph. Pracchi, 1941) later d) artificially dammed (ProgettoDighe.it, undated); e) tourists at the Miage Lake in Veny Valley (Monte Bianco massif, ph. http://culturedalmondo.blogspot.it, undated); f) informative panel on the path through glacier lakes at the Bessanese Glacier (ph. Rogliardo, 2014).

7.3.2 Potentially hazardous processes and/or situations related to the presence of glacier lakes

In some cases, the presence of a glacier lake can be associated to hazard related issues. The most well-known cases of lakes with associated hazard potential in the Western Italian Alps identified from the beginning of the XX century until now have already been described in chapter 4 and are: Galambra in the Cottian Alps (Peretti, 1935), Locce in the Pennine Alps (Haeberli & Epifani, 1986; Tropeano et al., 1999; fig. 7.10a and b), Rutor in the Graian Alps (Dutto & Mortara, 1992; fig. 7.10c), Miage in the Graian Alps (Deline et al., 2004; Diolaiuti et al., 2006; fig. 7.10d), Belvedere in the Pennine Alps (Mortara & Tamburini, 2009; fig. 7.10e), Rocciamelone in the Graian Alps (Vincent et al., 2010; fig. 7.10f). Both the lake types and related hazardous conditions are very different and each case was analyzed in detail in the respective papers for better understanding the pre-conditions affecting their stability and the drainage processes. A very recent documented but not studied case with no consequences dates from August 2016. It refers to the outburst of the lake at the Gran Croux Glacier in the Gran Paradiso Chain (Graian Alps) and was described by a ranger of the Gran Paradiso National Park (FMS, 2016).

In the past, the drainage of the mentioned glacier lakes was possible through en-/or subglacial channels or artificial pumping.

In the future, the formation of new lakes at higher elevation could increase the hazard potential of high mountain areas. The possible chain effects due to the presence of many lakes in the same basin has to be considered, as well as their opposite and positive effects as hazard protection. Moreover, as suggested by Haeberli et al. (2016), in a de-glaciating environment, the areas producing rock avalanches that will reach lakes will increase. Thanks to the creation of existing lake inventories and the modeling of potential new ones, fundamental early analysis can be done for the assessment and management of the hazard. Valleys with the presence of several lakes can be easily identified and also lakes surrounded by steep rock walls and unstable hanging glaciers or séracs.

In the Western Italian Alps, if the mentioned factors (evidence of ice/rock instabilities and/or presence of several lakes in the same valley) are considered, it is possible to give a general indication of the areas that needs a greater attention. Surely, the East side of the Monte Rosa Massif above the hamlet of Macugnaga is a very active area (Fischer et al., 2012) with evidence of both ice and rock falls (the most recent is the one from the Punta Tre Amici, December 2015; fig. 7.10b), the presence of the moraine-dammed Locce Lake (fig. 7.10a) and the debris-covered Belvedere Glacier with supraglacial ephemeral lakes on its surface (fig. 7.10e). The potential presence of two overdeepenings under the Triolet and Pré de Bar glaciers in the Ferret Valley has also to be considered and detailed investigations for verifying the real presence of the corresponding subglacial morphologies could be carried out. In these cases, the hazard could be due to the potential rockfalls generating from the high and steep walls in the surroundings (Ravanel et al., 2017). The same could be done for the case of the Rutor Glacier considering the presence of several lakes in the proglacial area (fig. 7.10c).

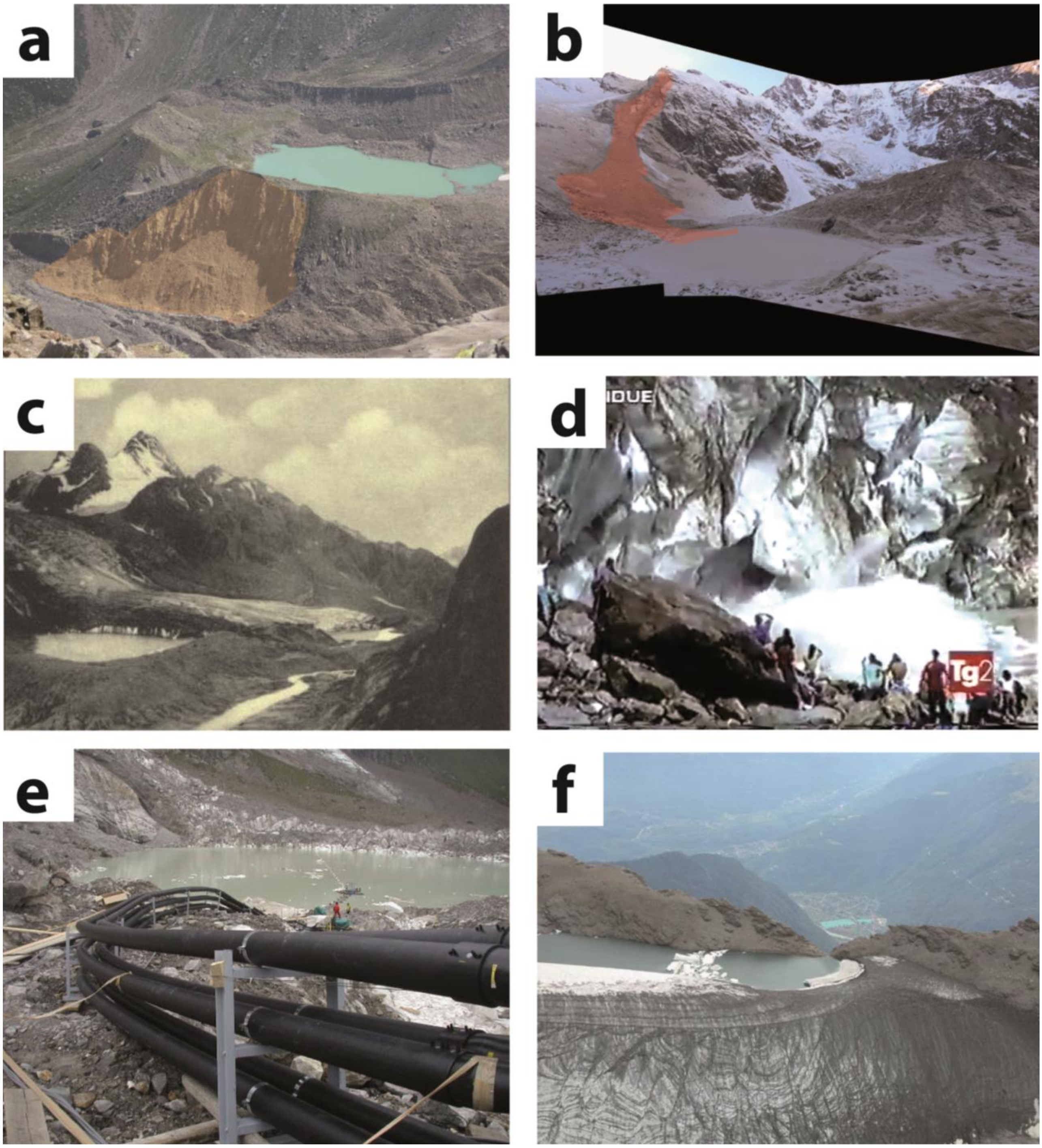


Figure 7.10 - Potentially hazardous processes and/or situations connected to glacier lakes: a) evidence of the erosive action (orange area) on the frontal moraine at the Locce Lake (ph. Alberto, 2010); b) panorama of the landslide (red area) from the Punta Tre Amici (Monte Rosa massif) reaching Locce Lake (ph. Chiarle, 2015); c) Santa Margherita ice-dammed lake at Rutor Glacier (ph. Gabinio, 1886); d) ice blocks falling into the Miage Lake causing a surge wave threatening several tourists (frame from the TG2 video, 1994); e) artificial pumping at the Effimero Lake (Belvedere Glacier, Monte Rosa massif; ph. Dipartimento Protezione Civile Nazionale, 2002); f) ice-dammed lake at the Rocciamelone Glacier (Dipartimento Protezione Civile Nazionale, 2004).

8 CONCLUSION AND FUTURE PERSPECTIVES

8.1 MAJOR FINDINGS

Here the major findings of the PhD research are summarized according to the research questions formulated in section 1.2.

How is it possible to reconstruct the formation and evolution of glacier lakes since the end of the LIA?

- Integrated information from different data sources has proven to be essential for restrospective analyses of deglaciating landscapes.
- In particular, the integration of historical topographic maps, aerial orthophotos and reports of the annual glaciological surveys is suitable for the reconstruction of the past formation and evolution of glacier lakes.
- Both quantitative and qualitative data have been extracted in order to have the widest possible overview of the phenomena at the temporal and spatial dimension.
- Obviously the limitation of the data sources has also to be taken into account both from a quantitative (accuracy of the morphometric parameters) and qualitative (identification of the lakes) point of view.

Where and when did glacier lakes appear since the end of the LIA and how did they develop through time?

- Thanks to the creation of 6 different glacier inventories, a total number of 254 glacier lakes have been identified from the end of the Little Ice Age until now in the Western Italian Alps. Geographic, morphometric and geomorphologic information concerning each time step have been provided.
- In general, lakes are localized mainly in the Graian Alps (Rutor-Lechaud, Gran Sassière-Tsanteleina and Gran Paradiso chains) and in the Pennine Alps (Monte Rosa Group). About 70% ofb the inventoried lakes are localized between 2600 and 3000 m a.s.l., the mean elevation is around about 2700 m.
- About 80% of the lakes are dammed by bedrock and are localized in glacier-bed overdeepenings excavated by glacier erosion in the past. Of the remaining lakes, 19% are dammed by moraines of the

LIA and of the two small glacier readvances which occurred in the 1920s and 1970s. The last 1% is represented by supraglacial lakes located mainly on debris-covered glaciers.

- The created database contains more than 700 records describing lakes of the Western Italian Alps from 1928 until now. Series of more than 40 records concerning a single lake and covering the entire period can be found, adding fundamental information to those extracted from the maps and the orthophotos.
- Different morphometric processes have been identified thanks to a retrospective analysis on the changes of the lake population in the considered time period. The appearance of new lakes, as well as the enlargement of the existing ones, is mainly due to glacier retreat, while the disappearance of lakes is mainly due to infilling processes by sediments.

Where are future glacier lakes likely to appear?

- The GlabTop2 model was tested on the most intensively glacierized region of Italy, the Aosta Valley Region (36% of the whole Italian glacier coverage). 46 potential future overdeepenings have been modeled, covering a total area of 3.1 ± 0.9 km^2.
- The majority of the overdeepenings are located in the Monte Rosa – Cervino massif and in the Gran Paradiso chain, the same mountain sectors where most of the existing lakes are located. Their position corresponds to the flattest part of the existing glaciers (<5°), mostly at frontal parts of them or in wide accumulation areas.
- The average of the modeled overdeepenings > 10,000 m^2 has an area of 68,000 m^2, a volume of $1.2 \cdot 10^6$ m^3 a mean depth exceeding 10 m. Seven overdeepenings larger than $1 \cdot 10^6$ m^3 accounted for 89% of the total volume and two larger than $10 \cdot 10^6$ m^3 for 45% (underneath the Rutor and the Triolet glaciers).
- Considering the possible future landscape evolution, it has to be mentioned that, compared to the total glacier volumes (7.3 km^3, referred to 1991), the calculated possible future overdeepenings volume (0.06 km^3) is about 0.8%. The smallest and shallowest overdeepenings will probably appear in the coming years because of glacier retreat, the largest and deepest may still remain occupied by the glaciers during the next few decades.

How can the quality and reliability of modeled glacier-bed topographies be evaluated?

- An additional new method, named “backward validation”, for validating model results has been proposed. It is based on the use of historical datasets as test data for the modelisation. Moreover, it is based on the assumption that from the year of the historical data acquisition until now glaciers have retreated and new lakes and glacially sculpted morphologies have become exposed. The main idea is to compare modeled overdeepenings and modeled bedrock with the existing real situation.
- The backward validation has proven to be a useful additional method allowing additional considerations on the suitability of the model in the test area with respect to the only forward validation with the GPR data.
- Obviously, GPR surveys remain the most used and useful validation method of the still not exposed overdeepenings
- As already demonstrated for other glacierized regions of the world, also for the Italian side of the Alps (represented by the Aosta Valley test region) the location of the modeled overdeepeenings is robust, a higher level of uncertainty remains considering the dimensions of the overdeepenings.

8.2 CONCLUSIONS

This thesis on the morphodynamics of glacier lakes resulting from continued glacier shrinkage in a mountain region enabled the creation and test of a targeted research methodology useful for both, inventory and description of past evidence and also for assessment and interpretation of future scenarios in the Western Italian Alps.

A schematic overview of the research methodology (fig. 8.1) summarizes procedures and main findings of the thesis. The yellow rectangles represent the input data, the blue ones are the output data and the green ones are the final results obtained. The lines connecting the different rectangles are the applied methodologies described in the related sections.

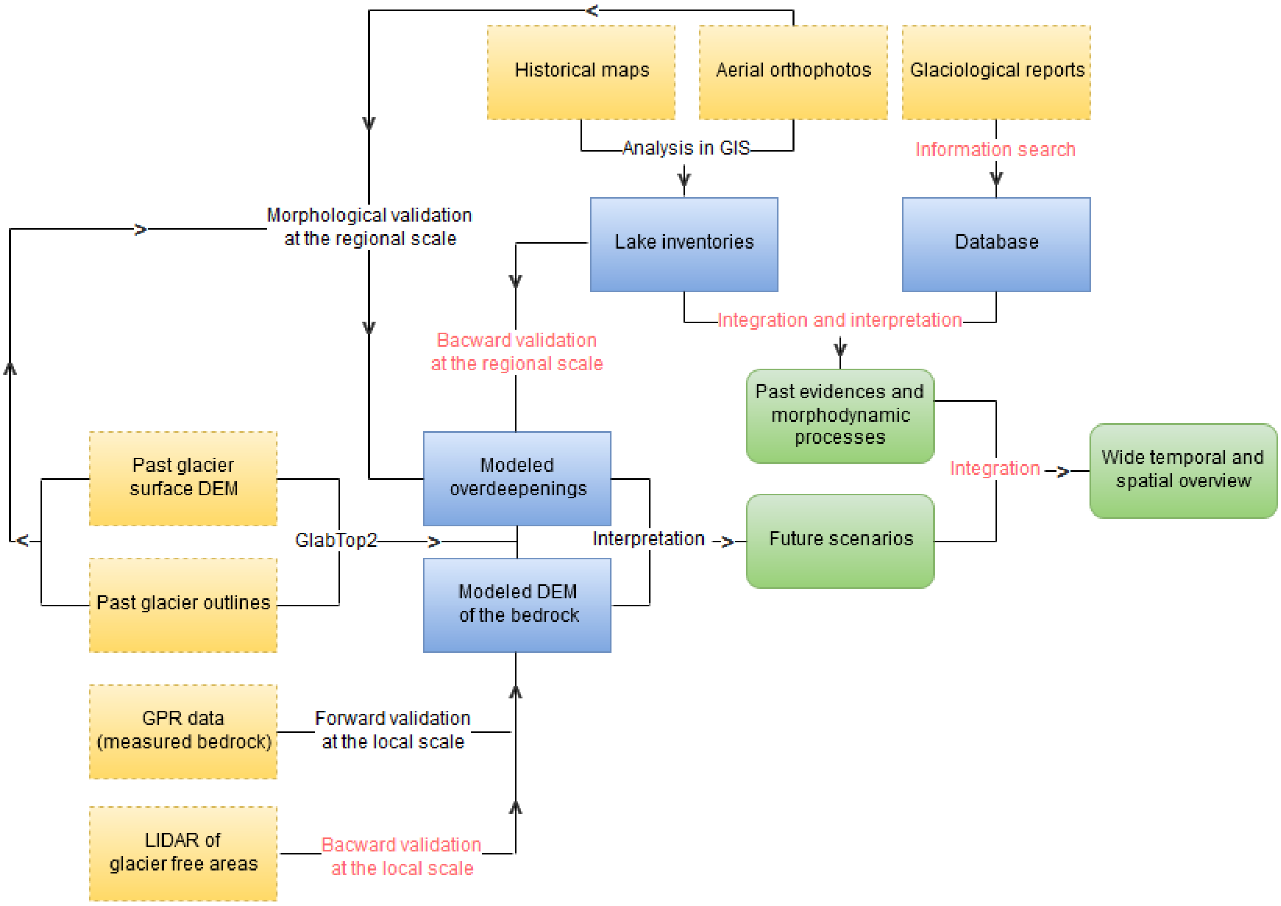


Figure 8.1 - Schematic overview of the elements of the present thesis and their connections.

As it is clearly evident by the schematic overview, an integration of a diversity of input data has been carried out: maps, orthophotos, glaciological reports, DEMs, glacier outlines, GPR data. Some of them belong to the category of the historical data and the others refer to the category of data produced by Information Technologies (IT).

Moreover, the methodology proposed in this PhD project represents an enhanced solution for integrating and harmonizing existing and well-established methodologies developed in other studies (words in black) together with new ones here proposed (words in orange).

The integration of historical maps and aerial orthophotos has proven to be suitable for the creation of glacier lake inventories related to different time steps covering an extended time period characterized by substantial modification of the Alpine cryosphere. Information sought from the annual glaciological surveys and successively stored and organized in a dedicated database, represents fundamental confirmation of the results obtained by the creation of inventories and often constitutes an additional source of essential information, otherwise unavailable, in view of the reconstruction of lake formation and evolution and identification of related morphodynamic processes. The described methodologies could be applied to other regions where similar data sources are available taking into account that for this first part of the research project all the data were manually analysed.

This approach using past evidence related to the investigation of the phenomenon “glacial lake” allows to go back in time approximately to the end of the LIA from a temporal point of view and to survey a wide area from a spatial point of view. Moreover, the use of different data sources permits to deepen the knowledge in the dimension of the details of the sought information, there are lakes for which precise description of the processes and aspect, morphometric parameters, photos and sketches are available.

In the second part of the research project, the GlabTop2 model was applied to the glaciers of the Aosta Valley Region. The obtained results offer information about ice volumes for the largest glacierized region of Italy and about the location of potential future lakes. This information is significant for both, the scientific community because this model was never applied to the Italian cryosphere and the administrative stakeholders of the region for further application in the field of water and hazard management.

Other than validate the results with the well-known methodologies (GPR surveys and morphological criteria), a new way for the validation was proposed and named “backward approach”. The principle is based on the use, as test of the modeling, of historical datasets (DEM and glacier outlines) so that the model results (overdeepenings and bedrock topography) can be compared with the reality (existing lakes and morphologies) for these areas left by the glacier in the years between the input data survey and now. For the application of the described approach it is necessary to have lake inventories and recent DEMs available for making the comparison. This proves again the importance of creating lake inventories.

Results obtained in this first part of the research project, regional inventories on lakes formed in the past, contribute to enhancing the knowledge of glacier lakes in the European Alps and to the filling of the gap for the Italian Alps. Moreover, they were fundamental for the validation of the results obtained by the model in second part of the research. The modeling of potential future lakes completes the present study. Integrating the results for the past and for the future a wide temporal and spatial overview of the phenomenon is given in the present thesis for the Western Italian Alps, constituting a first example for further similar studies in the Italian Alps but also elsewhere. Finally, preliminary consideration about the possible uses and potential hazards related to the presence of glacier lakes for the future are proposed considering uses and hazards identified in the past.

8.3 PERSPECTIVES FOR FUTURE RESEARCH

In the following, topics for future research are proposed and divided into three main groups that refer to “past evidence”, “future scenarios” and “opportunities and hazards” related to glacier lakes. In the first two groups, research topics connected both to knowledge/understanding and methodological enhancement are proposed. They derive from the identification of the gaps in the current state of the research combined with the results obtained by the present thesis.

Overview of glacier lakes from the end of the LIA until now

Not much was known about the formation and evolution of Italian glacier lakes due to glacier shrinkage since the end of the LIA. The present thesis aims at partially filling this gap focusing on the Western part of the Italian Alps, adding information to existing ones for the Lombardia Region (Galluccio et al., 1998) and Ortles-Cevedale Group (Salerno et al.,2014).

The proposed approach integrating different data sources allowed the reconstruction of the studied phenomenon at the regional scale and for a long time period. It would be interesting and useful to try to apply the same methodology to the rest of the Italian Alps (Central and Eastern) in order to have a complete overview of the development of glacier lakes through time and to even better understand their morphodynamics. The data sources used (historical maps of the IGMI, orthophotos and reports of the glaciological surveys) do not only cover the study area but the entire Italian territory and can thus be used to investigate the whole Italian Alps in order to produce national lake inventories related to different time steps.

The creation of Italian glacier lake inventories and their combined analysis with existing glacier inventories (CGI, 1961; Ajassa et al., 1994; 1997; Salvatore at al., 2015; Smiraglia et al., 2015) would enhance the knowledge about the effects of continued glacier shrinkage on the alpine landscape.

Moreover, following the example of Salerno et al. (2014), multitemporal analysis on the changes in glacier lakes population associated with changes in climatic conditions (in particular temperature and precipitation) in the different alpine sectors could help to comprehend the more general impact of climate change in mountain areas.

From a methodological point of view, additional data sources should be investigated in order to add additional information to those extracted from the present approach. In particular, in order to carry on the study of the formation and evolution of glacier lakes in the present, attention should be paid to the new datasets of the optical satellite from ESA, Sentinel-2. Thanks to the relatively high resolution (10 m) of the sensor in the NIR infrared and blue bands, the NDWI index (Huggel et al., 2002) can be applied for the detection of glacier lakes like those identified in the present study.

The proposed approach and related implementation could also be applied in other mountain regions, such as the French, Swiss and/or Austrian Alps, where similar data sources for the considered time period are available.

Potential future lakes

The GlabTop approach is currently widely used and potential future lakes in some important mountain regions of the world have already been modeled (Linsbauer et al., 2012; Frey et al., 2016; Colonia et al., 2017). Italian glaciers had not been taken into account before the present PhD project. Testing the GlabTop2 for Aosta Valley glaciers has allowed to provide an indication of ice thicknesses, to predict potential locations of future glacier lakes for the most extensively glacierized region of Italy and to demonstrate its suitability also for Italian glaciers. To extend the modeling to the rest of the Italian cryosphere would be of considerable significance both for estimating at a national level the total amount of water stored in the glaciers and for understanding how the alpine environment will look like in the future.

Combining the analysis of the location of modeled lakes with glacier retreat scenarios will allow to define the approximately year or decades during which the potential lakes will appear (Colonia et al., 2017).

Considering the proposed backward approach for the model results validation, further implementation could be done. In the present research a historical DEM of 1991 was used covering the entire Aosta Valley. Additional validation but also calibration of the model could be achieved if older DEMs could be produced, for example by aerial photos. Preliminary elaboration of aerial photo stereo pairs of the 1954 GAI flight have been performed on selected glaciers where significant glacier lakes have formed in bedrock overdeepenings (Rutor and Indren glaciers). The main problems are connected to the quality of the photographs and to the missing calibration certificate of the camera. Errors of the extracted DEMs have to be carefully taken into account.

Opportunities and hazards related to glacier lakes

As anticipated in paragraph 7.3, the integration and the interpretation of the results from the analysis of past evidence and the modeled future scenarios will be of great benefit in order to identify potential opportunities and hazards connected to the presence of glacier lakes in the studied regions. The wide spatial overview allows the identification of specific glacier lakes that can be subjected to the following actions.

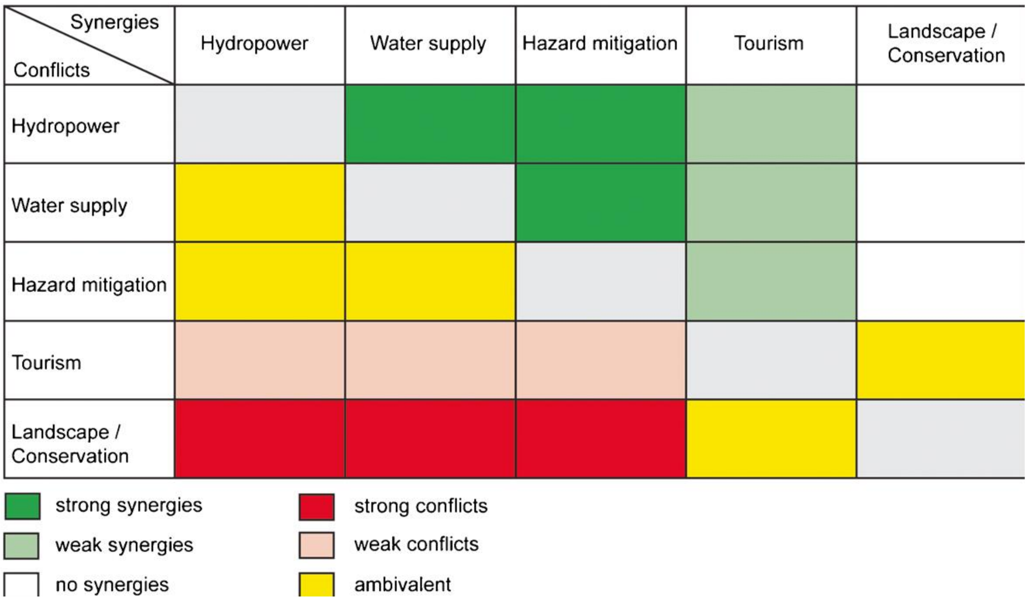
Exploitation as water reservoir. New glacier lakes will replace less than 1% of the present glaciers volume in the Western Italian Alps. Few of them could be used for freshwater supply for mountain huts and/or alpine hamlets, their potential exploitation has to be analyzed in detail considering different qualitative and quantitative aspects (Colombo et al., 2017). Firstly, the lake volume has to be calculated, for example, by geophysical investigations. Analysis of the water quality by in-situ water sampling and laboratory analysis have to be achieved. Infrastructures (tunnels, dam) for water transport from the lake to the users have to be planned and corresponding investment calculated.

Exploitation for hydropower production. Hydroelectricity is of considerable significance for the economy of alpine regions, such as Switzerland or northern Italy (e.g. Piemonte and Aosta Valley). The presence of high altitude glacier lakes and the potential appearance on new ones represent an important opportunity for the enhancement of hydropower production in such regions by the construction of new dams. It requires unavoidable analysis of the future water supply evolution in the selected basin (precipitations and melt water from the glacier) in relation with climate change and the hydroelectric potential of the future artificially dammed lake (Terrier et al., 2011). Planning dam construction in high mountain areas in the presence of glacier and permafrost requires also detailed analysis of glacier and slope stabilities because of the potential impact waves produced by ice or rock avalanches into lakes. Moreover, feasibility studies of the project (including the ecologic impact on the environment) and cost/benefit analysis (that take into account the electricity price, maintenance and relationship with possible other uses of the lake water) are required.

Valorization through geotourism. The quality of the dynamic landscape of deglaciating Alps has been recognized as a great attraction for geotouristic purposes. For instance, the landscape beauty is not of immediate use since some assessment are required to develop proper plan for fruition. The application of geosite assessment methods adapted to the specific gemorphological landscape of glacier lakes is suggested (Reynard et al., 2007). Evaluation of parameters such as accessibility of the glacier lake area, the related hazard and vulnerability either by natural or human impacts can lead to the identification of best solutions for geotouristic appraisal of the geosite. This includes the realization of paths, hanging bridges, explanation panels and so one and all the actions to mitigate impacts on the glacial geosite.

Assessment and management of potential outburst. For the identification of hazardous lakes both remote sensing and in-situ investigations are required. Conditioning and triggering factors that has to be considered for the susceptibility and stability assessment (Portocarrero, 2014) are: 1) volume of the lake (by cartographic and bathymetric studies) that influence the magnitude of the flow; 2) glacier characteristics (slope, crevasses, fragmentation, thickness); 3) slope of the bedrock (by DEM analysis) that influence the glacier stability and the probability of failure; 4) geometry and structure of the moraine damming the lake (by identification of internal ice and evaluation of the erosion degree of the moraine, etc.); 5) length and slope of the valley downstream that influence the kinetic energy of the flood; 6) presence of hanging glaciers or seracs, calving processes or unstable rock slopes that can release materials (ice and/or rock) into the lake causing surge waves. Once the hazard has been assessed, its successive impact assessment is required. It refers to hazard modeling and mapping considering different scenarios of the event magnitude and the possible vulnerable human infrastructures and activities being involved (Haeberli et al., 2016c).

Finally, the hazard management has to be considered by establishing logistical access to the lake; implementation of safety measures (volume reduction by cutting the lake dam, construction of drainage tunnels, seepage by opening trenches), early warning system, evacuation plans and spreading of safety tips (Tamburini et al., 2003). In view of multiple uses of future lakes, both advantages and disadvantages have to be taken into account. Synergies and/or conflicts concerning future lakes development are possible, as Haeberli et al. (2016a) suggested, and all aspects have to be evaluated (geo-/ecosystems, human-environment relations, differing perceptions and perspectives). Matrix analysis, as the one proposed by Haeberli et al. (2016a) will help the participative planning and management of future lakes. Strong synergies exist for project that will consider the use of glacier lakes for water supply, hydropower production and flood retention. They could also partially increase the tourist value. On the other hand, the above mentioned uses can be in strong conflicts with the landscape conservation. Additional but weak conflicts and ambivalent relations exist, for example, between hazard prevention and tourist fruition and also between landscape conservation and tourism.



Synergies Conflicts	Hydropower	Water supply	Hazard mitigation	Tourism	Landscape / Conservation
Hydropower		🟩	🟩	▩	☐
Water supply	🟨		🟩	▩	☐
Hazard mitigation	🟨	🟨		▩	☐
Tourism	▧	▧	▧		🟨
Landscape / Conservation	🟥	🟥	🟥	🟨	

🟩 strong synergies
▩ weak synergies
☐ no synergies
🟥 strong conflicts
▧ weak conflicts
🟨 ambivalent

Figure 8.2 - Matrix of potential synergies and conflicts concerning the management of new lakes as proposed by Haeberli et al. (2016a).

REFERENCES

AA.VV. (2009) - *Ortoimmagini 1:10000 e modelli altimertrici - Linee Guida.* Comitato per le regole tecniche sui dati territoriali delle Pubbliche Amministrazioni, 154 pp.

Ageta, Y., Iwata, S., Yabuki, H., Naito, N., Sakai, A., Narama, C. & Karma, T. (2000) - *Expansion of glacier lakes in recent decades in the Bhutan Himalayas*. IAHS Publication, 264, 165–175.

Ajassa R., Biancotti A., Biasini A., Brancucci G., Caputo C., Pugliese F. & Salvatore M.C. (1994) - *Il catasto dei ghiacciai italiani: primo confronto tra i dati 1958 e 1989.* Quaternario, 7 (1), 497-502.

Ajassa R., Biancotti A., Biasini A., Brancussi G., Carton A. & Salvatore M. C. (1997) - *Changes in the number and area of Italian Alpine glaciers between 1958 and 1989*. Geografia Fisica e Dinamica Quaternaria, 20, 293-297.

Aliprandi L. & Aliprandi G. (2005) - *Le Grandi Alpi nella Cartografia (1482-1885). Volume I. Storia della cartografia alpina.* Collana Antica Cartografia. Priuli & Verlucca Editori, 360 pp.

Allen S. K., Schneider D. & Owens I.F. (2009) - *First approaches towards modelling glacial hazards in the Mount Cook region of New Zealand's Southern Alps*. Natural Hazards Earth System Science, 9, 481-499.

Ashley G. M. (1995) - *Glaciolacustrine Environments*. In: Modern Glacial Environments. Porcesses, Dynamics and Sediments. Editor Menzies J. Glacial Enviornments: Volume 1, 417-444.

ASPRS – American Society of Photogrammetry and Remote Sensing (2014) - *ASPRS Positional Accuracy Standards for Digital Geospatial Data*. Photogrammetric Engineering & Remote Sensing, 81 (3), 26 pp.

Bolch T., Buchroithner M. F., Peters J., Baessler M., & Bajracharya S. (2008) - *Identification of glacier motion and potentially dangerous glacial lakes in the Mt. Everest region/Nepal using spaceborne imagery*. Natural Hazards and Earth System Sciences, 8, 1329-1340.

Bolch T., Peters J., Yegorov A., Pradhan B., Buchroithner M. & Blagoveschchensky V. (2011) - *Identification of potentially dangerous glacial lakes in the northern Tien Shan*. Natural Hazards, 59 (3), 1691-1714.

Capps D. M. & Clague J. J. (2014) - *Evolution of glacier-dammed lakes through space and time ; Brady Glacier, Alaska, USA*. Geomorphology, 210, 59-70.

Carrivick J. L. & Tweed F. S. (2013) - *Proglacial lakes: character, behavior and geological importance*. Quaternary Science Reviews, 78, 34-52.

Carton A., Baroni C. & Seppi R. (2003) - *La cartografia antica ed attuale negli studi di glaciologia e di geologia glaciale*. Bollettino dell'Associazione Italiana di cartografia, vol. 117-119, 376-396.

CGI – Comitato Glaciologico Italiano (1928-1977) - *Relazioni delle campagne glaciologiche - Reports of the glaciological surveys*. Bollettino del Comitato Glaciologico Italiano, Serie I, vol. 1-25 and Serie II, vol. 1-25.

CGI – Comitato Glaciologico Italiano (1978-2015) - *Relazioni delle campagne glaciologiche - Reports of the glaciological surveys*. Geografia Fisica e Dinamica Quaternaria, vol. 1-38.

CGI-CNR – Comitato Glaciologico Italiano & Consiglio Nazionale delle Ricerche (1961) - *Catasto dei Ghiacciai Italiani, Anno Geofisico Internazionale 1957-1958. Ghiacciai del Piemonte*. Comitato Glaciologico Italiano, Torino, vol. 2, 324 pp.

Čiamporová-Zaťovičová Z. & Čiampor Jr F. (2017) - *Alpine lakes and ponds - a promising source of high genetic diversity in metapopulations of aquatic insects*. Inland Waters, 7:1, 109-117.

Citterio M., Diolaiuti G., Smiraglia C., D'Agata C., Carnielli T., Stella G. & Siletto G. B. (2007) - *The fluctuations of Italian glaciers during the last century: a contribution to knowledge about alpine glacier changes*. Geografiska Annaler Series A: Physical Geography, 89 (3), 164-182.

Colombo N., Sambuelli L., Comina C., Colombero C., Giardino M., Gruner S., Viviano G., Vittori Antisari L. & Salerno F. (2017) - *Mechanisms linking active rock glaciers and impounded surface water formation in high-mountain areas*. Earth Surface Processes and Landforms, 43, 417-431.

Colonia D., Torres J., Haeberli W., Schauwecker S., Braendle E., Giraldez C. & Cochachin A. (2017) - *Compiling an Inventory of Glacier-Bed Overdeepenings and Potential New Lakes in De-Glaciating Areas of the Peruvian Andes: Approach, First Results, and Perspectives for Adaptation to Climate Change*. Water, 9, 336, 18 pp.

Deline P., Diolaiuti G., Kirkbride M., Mortara G., Pavan M., Smiraglia C. & Tamburini A. (2004) - *Drainage of ice-contact Miage Lake (Mont Blanc Massif, Italy) in September 2004*. Geografia Fiscia e Dinamica Quaternaria, 27, 113-119.

Diolaiuti G., Bocchiola D., Vagliasindi M., D'Agata C. & Smiraglia C. (2012) - *The 1975-2005 glacier changes in Aosta Valley (Italy) and the relations with climate evolution*. Progress in Physical Geography, 36 (6), 764-785.

Diolaiuti G., Citterio M., Carnielli T., D'Agata C., Kirkbride M., & Smiraglia C. (2006) - *Rates, processes and morphology of freshwater calving at Miage Glacier (Italian Alps)*. Hydrological Processes, 20 (10), 2233-2244.

Dutto F. & Mortara G. (1992) - *Rischi connessi con la dinamica glaciale nelle Alpi Italiane*. Geografia Fisica e Dinamica Quaternaria, 15, 85-99.

EEA – European Environment Agency (2004) - *Impact of Europe's changing climate*, 107 pp, ISBN: 92-9167-692-6.

Emmer A., Klimeš J., Mergili M., Vilímek V., & Cochachin A. (2016) - *822 lakes of the Cordillera Blanca: An inventory, classification, evolution and assessment of susceptibility to outburst floods*. Catena 147, 269-279.

Emmer A., Merkl S. & Mergili M. (2015) - *Spatiotemporal patterns of high-mountain lakes and related hazards in western Austria*. Geomorphology, 246, 602-616.

Emmer A., Vilímek V., Klimeš J. & Cochachin A. (2014) - *Glacier retreat, lakes development and associated natural hazards in Cordilera Blanca, Peru*. In: Landslides in cold regions in the context of climate change, 231-252.

Farinotti D., Huss M., Bauder A., Funk M. & Truffer M. (2009) - *A method to estimate the ice volume and ice-thickness distribution of alpine glaciers*. Journal of Glaciology, 55 (191), 422-430.

Farinotti, D., Brinkerhoff, D. J., Clarke, G. K. C., Fürst, J. J., Frey, H., Gantayat, P., Gillet-Chaulet, F., Girard, C., Huss, M., Leclercq, P. W., Linsbauer, A., Machguth, H., Martin, C., Maussion, F., Morlighem, M., Mosbeux, C., Pandit, A., Portmann, A., Rabatel, A., Ramsankaran, R., Reerink, T. J., Sanchez, O., Stentoft, P. A., Singh Kumari, S., van Pelt, W. J. J., Anderson, B., Benham, T., Binder, D., Dowdeswell, J. A., Fischer, A., Helfricht, K., Kutuzov, S., Lavrentiev, I., McNabb, R., Gudmundsson, G. H., Li, H., and Andreassen, L. M. (2017) - *How accurate are estimates of glacier ice thickness? Results from ITMIX, the Ice Thickness Models Intercomparison eXperiment*. The Cryosphere, 11, 949-970.

FGDC – Federal Geographic Data Committee (1998) - *Geospatial Positioning Accuracy Standards. Part 3: National Standard For Spatial Data Accuracy*. Subcommittee for Base Cartographic Data, 28 pp.

Fischer L., Huggel C., Kääb A. & Haeberli W. (2012) - *Slope failures and erosion rates on a glacierized high-mountain face under climatic changes*. Earth Surface Processes and Landforms, 11 pp.

FMS – Fondazione Montagna Sicura (2016) - *Bilancio sociale e di Missione 2016*. 68 pp.

Frey H. (2011) - *Compilation and Applications of Glacier Inventories using Satellite Data and Digital Terrain Information*. Schriftenreihe Physische Geographie, Glaziologie und Geomorphodynamik, 62, 196 pp.

Frey H., Haeberli W., Linsbauer A., Huggel C. & Paul F. (2010a) - *A multi-level strategy for anticipating future glacier lake formation and associated hazard potentials*. Natural Hazards and Earth System Sciences, 10, 339-352.

Frey H., Huggel C., Paul F. & Haeberli W. (2010b) - *Automated detection of glacier lakes based on remote sensing in view of assessing associated hazard potentials*. In: Kaufmann V. & Sulzer W. (Eds.), Proceedings of the 10th International Symposium on High Mountain Remote Sensing Cartography. Grazer Schriften der Geographie und Raumfoschung, 45, 261-272.

Frey H., Machguth H., Huss M., Huggel C., Bajracharya S., Bolch T., Kulkarni A., Linsbauer A., Salzmann N. & Stoffel M. (2014) - *Estimating the volume of glaciers in the Himalayan–Karakoram region using different methods*. The Cryosphere, 8, 2313-2333.

Galluccio A. (1998) - *I nuovi laghi proglaciali lombardi.* Terra glacialis, 1, 133-151.

Gardelle J, Arnaud Y. & Berthier E. (2011) - *Contrasted evolution of glacial lakes along the Hindu Kush Himalaya mountain range between 1990 and 2009*. Global and Planetary Change, 75, 47-55.

Giardino M., Mortara G. & Chiarle M. (2017) - *Glaciers of Valle d'Aosta and Piemonte Regions: Records of Present And Past Environmental and Climate Change*. In: Soldati M. & Marchetti M. Landscapes and Landforms of Italy. World Geomorphological Landscapes, 12 pp.

Haeberli W. & Epifani F. (1986) - *Mapping the distribution of buried glacier ice - An example from Lago delle Locce, Monte Rosa, Italian Alps*. Annals of Glaciology, 8, 78-81.

Haeberli W., Buetler M., Huggel C., Lehmann Friedli T., Schaub Y. & Schleiss A. J. (2016a) - *New lakes in deglaciating high-mountain regions – opportunities and risks*. Climatic Change, 139 (2), 201-214.

Haeberli W. & Hoelzle M. (1995) - *Application of inventory data for estimating characteristics of and regional climate-change effects on mountain glaciers: a pilot study with the European Alps*. Annals of Glaciology, 21, 206-212. Russian translation in: Data of Glaciological Studies, Moscow, 82, 116-124.

Haeberli W., Hoelzle M., Paul F. & Zemp M. (2007) - *Integrated monitoring of mountain glaciers as key indicators of global climate change: the European Alps*. Annals of Glaciology, 46, 150-160.

Haeberli W., Linsbauer A., Cochachin A., Salazar C. & Fischer U. H. (2016b) - *On the morphological characteristics of overdeepenings in high-mountain glacier beds*. Earth Surface Processes and Landforms, 41, 1980-1990.

Haeberli W., Schaub Y. & Huggel C. (2016c) - *Increasing risks related to landslides from degrading permafrost into new lakes in de-glaciating mountain ranges*. Gemorphology, 293, 405-417.

Hanshaw M. N. & Bookhagen B. (2014) - *Glacial areas, lake areas, and snow lines from 1975 to 2012: status of the Cordillera Vilcanota, including the Quelccaya Ice Cap, northern central Andes, Peru*. The Cryosphere, 8, 359-376.

Harrison W.D., Osipova G.B., Nosenko G.A., Espizua L., Kääb A., Fischer L., Huggel C., Burns P.A.C., Truffer M. & Lai A.W. (2014) - *Glacier surges*. In: Haeberli, W., Whiteman, C. (Eds.), Snow and Ice-related Hazards, Risks and Disasters. Elsevier, 437-485.

Huggel C., Kääb A., Haeberli W., Teysseire P. & Paul F. (2002) - *Remote sensing based assessment of hazards from Glacier lake outbursts: a case study in the Swiss Alps*. Canadian Geotechnical Journal, 39, 316-330.

Huss M. & Farinotti D. (2012) - *Distributed ice thickness and volume of all glaciers around the globe*. Journal of Geophysiscal research, 117, F04010.

IPCC (2013) - *Climate change 2013: The Physical Science Basis*. In: Stocker T.F., Qin D., Plattner G.K., Tignor M., Allen S.K., Boschung J., Nauels A., Xia Y., Bex V. & Midgley P.M. (Eds.) Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, 1535 pp.

Kapitsa V., Shahgedanova M., Machguth H.m, Severskiy I. & Medeu A. (2017*)* - *Assessment of evolution and risks of glacier lake outbursts in the Djungarskiy Alatau, Central Asia, using Landsat imagery and glacier bed topography modelling*. Natural Hazards and Earth System Sciences, 17, 1837-1856.

Komori J. (2008) - *Recent expansions of glacial lakes in the Bhutan Himalayas*. Quaternary International, 184, 177-186.

Linsbauer A., Frey H., Haeberli W., Machguth H., Azam M. F. & Allen S. (2016) - *Modelling glacier-bed overdeepenings and possible future lakes for glaciers in the Himalaya-Karakoram region*. Annals of Glaciology, 57 (71), 119-130.

Linsbauer A., Paul F. & Haeberli W. (2012) - *Modeling glacier thickness distribution and bed topography over entire mountain ranges with GlabTop: Application of a fast and robust approach*. Journal of Geophysical Research, 117, F03007.

Linsbauer A., Paul F. & Hoelzle M. (2009) - *The Swiss Alps Without Glaciers - A GIS-based Modelling Approach for Reconstruction of Glacier Beds*. In: Purves R., Gruber S., Straumann R. & Hengl T. (Eds.) Geomorphometry 2009 Conference Proceedings. University of Zurich, 243-247.

Loriaux T. & Casassa G. (2012). *Evolution of glacial lakes from the Northern Patagonia Icefield and terrestrial water storage in a sea-level rise context*. Global and Planetary Change, 102, 33-40.

Lucchesi S., Fioraso G., Bertotto S. & Chiarle M. (2014) - *Little Ice Age and contemporary glacier extent in the Western and South-Western Piedmont Alps (North-Western Italy)*. Journal of Maps, 10 (3), 409-423.

Marazzi S. (2005) - *Atlante orografico delle Alpi. SOIUSA - Suddivisione orografica internazionale unificata del Sistema Alpino*. Priuli & Verlucca Editori, Ivrea, 416 pp.

Mergili M., Müller J. P. & Schneider J. F. (2013) - *Spatio-temporal development of high-mountain lakes in the headwaters of the Amu Darya River (Central Asia)*. Global and Planetary Change, 107, 13-24.

Minora U., Bocchiola D., D’Agata C., Maragno D., Mayer C., Lambrecht A., Vuillermoz E., Senese A., Compostella C., Smiraglia C. & Diolaiuti G. (2016) - *Glacier area stability in the Central Karakoram*

National Park (Pakistan) in 2001-2010: The "Karakoram Anomaly" in the spotlight. Progress in Physical Geography, 40 (5), 629-660.

Mortara G. & Tamburini A. (2009) - *Il Ghiacciaio del Belvedere e l'emergenza del Lago Effimero*. Società Meteorologica Subalpina, Collana "Memorie dell'Atmosfera", 8, 192 pp.

NELAK (2013) - *Neue Seen als Folge des Gletscherschwundes im Hochgebirge - Chancen und Risiken. Formation des nouveux lacs suite au recul des glaciers en haute montagne – chances et risques*. Forschungsbericht NFP 61. Haeberli, W., Bütler M., Huggel C., Müller H. & Schleiss A. (Eds.). Zurich, 300 pp.

Oerlemans J. (2001) - *Glaciers and climate change*. Balkema Publishers, Rotterdam.

Orombelli G. (2005) - *Il Ghiacciaio del Rutor (Valle d'Aosta) nella Piccola Età Glaciale*. Geografia Fisica e Dinamica Quaternaria, Suppl. VII, 239-251.

Paterson, W. (1994) - *The physics of glaciers*. 3rd Edn., Pergamon Press, Oxford, New York, Tokyo, 1994, 481 pp.

Paul F. & Linsbauer A. (2012) - *Modeling of glacier bed topography from glacier outlines, central branch lines, and a DEM*. International Journal of Geographical Information Science, 26:7, 1173-1190.

Paul F., Frey H. & Le Bris R. (2011) - *A new glacier inventory for the European Alps from Landsat TM scenes of 2003: challenges and results*. Annals of Glaciology, 52(59), 144-152.

Paul F., Kääb A. & Haeberli W. (2007) - *Recent glaciers changes in the Alps observed by satellite: consequences for future monitoring strategies*. Global and Planetary Change, 56, 111-122.

Paul F., Kääb A., Maisch M, Kellenberger T. & Haeberli W. (2004) - *Rapid disintegration of Alpine glaciers observed with satellite data*. Geophysical Research Letters, 31 (21), L21402, 1-4.

Portocarrero C. A. (2014) - *The glacial lake handbook: reducing risk from dangerous glacial lakes in the Cordillera Blanca, Peru*. Technical Report, United States Agency for International Development, Global Climate Change Office, Climate Change Resilient Development Project Washington, DC, 68 pp.

Pelifini M. (2004) - *Tavola 43. Laghi glaciali*. In: Italia. Atlante dei tipi geografici, Firenze, Istituto Geografico Militare, 245-249.

Peretti L. (1935) - *Les lacs de barrage glaciaire et le vidage du lac de Galambra (Massif d'Ambin).* Revue de géographie alpine, 23 (3), 635-654.

Ravenel L., Magnin F. & Deline P. (2017). *Impacts of the 2003 and 2015 summer heatwaves on permafrost-affected rock-walls in the Mont Blanc massif*. Science of the Total Environment, 609, 132-143.

Reynard E., Fontana G., Kozlik L. & Scapozza C. (2007) - *A method for assessing scientific and additional value of geomorphosites*. Geographica Helvetica 62 (3), 148-158.

Rüesch R. (2013) - *Validierung und Anwendung einer mehrstufigen Strategie zur Identifikation zukünftiger Gletscherseen*. Master thesis. University of Zurich. 113 pp.

Sacco F. (1918a) - *Il glacialismo antico e moderno della Valpellina*. Atti della Società di Scienze Naturali, Vol. LVII, 28 pp.

Sacco F. (1918b) - *I ghiacciai italiani del gruppo del Monte Bianco*. Bollettino del Comitato Glaciologico Italiano, Serie I, Num. 3, 21-105.

Sacco F. (1918c) - *Il glacialismo antico e moderno del Cervino*. Atti della Reale Accademia delle Scienze di Torino, Vol. 53, 31 pp.

Sacco F. (1920) - *Il glacialismo antico e moderno nelle alte valli di Ayas (Evançon) e di Gressoney (Lys)*. Bollettino del Reale Comitato geologico d'Italia, Vol. XLVII, Fasc. I-IV, 226 pp.

Sacco F. (1921) - *Il glacialismo nel Gruppo del Gran Paradiso*. Bollettino del Comitato Glaciologico Italiano, Serie I, Num. IV, 121-169.

Sacco F. (1922) - *Il glacialismo nel Gruppo del Gran Paradiso*. Bollettino del Comitato Glaciologico Italiano, Serie I, Num. V, 53-129.

Sacco F. (1930) - *Il glacialismo nelle valli Sesia, Strona, Anza e nell'Ossola*. Ministero dei lavori pubblici, Servizio Idrografico, Ufficio idrografico del Po - Parma. N. 10, Vol. 4, 106 pp.

Salerno F., Gambelli S., Viviano G., Thakuri S., Guyennon N., D'agata C., Diolaiuti G., Smiraglia C., Stefani F., Bocchiola D. & Tartari G. (2014) - *High alpine ponds shift upwards as average temperatures increase: A case study of the Ortles-Cevedale mountain group (Southern Alps, Italy) over the last 50 years*. Global and Planetary Change, 120, 81-91.

Salerno F., Thakuri S., D'Agata C., Smiraglia C., Manfredi E. C., Viviano G. & Tartari G. (2012) - *Glacial lake distribution in the Mount Everest region: Uncertainty of measurement and conditions of formation*. Global and Planetary Change, 92-93, 30-39.

Salerno F., Thakuri S., Guyennon N., Viviano G., & Tartari G. (2016) - *Glacier melting and precipitation trends detected by surface area changes in Himalayan ponds*. The Cryosphere, 10, 1433-1448.

Salvatore M. C., Zanoner T., Baroni C., Carton A., Banchieri F. A., Viani C., Giardino M. & Perotti L. (2015) - *The state of Italian glaciers: a snapshot of the 2006-2007 hydrological period*. Geografia Fisica e Dinamica Quaternaria, 38 (2), 175-198.

Schomacker A. (2010) - *Expansion of ice-marginal lakes at the Vatnajökull ice cap, Iceland, from 1999 to 2009*. Geomorphology 119, 232-236.

Smiraglia C., Azzoni R. S., D'agata C., Maragno D., Fugazza D. & Diolaiuti G. A. (2015) - *The evolution of the Italian glaciers from the previous data base to the New italian Inventory. Preliminary considerations and results*. Geografia Fisica e Dinamica Quaternaria, 38 (1), 79-87.

Stokes C.R., Popovnin V., Aleynikov A., Gurney S.D. & Shahgedanova M. (2007) - *Recent glacier retreat in the Caucasus Mountains, Russia, and associated increase in supraglacial debris cover and supra-/proglacial lake development*. Annals of Glaciology, 46, 195-203.

Strozzi T., Dammert P., Wegmüller U., Martinez J. M., Askne J., Beaudoin A. & Hallikainen M. (2000) - *Landuse Mapping with ERS SAR Interferometry*. Transactions on Geoscience and Remote Sensing, 38 (2), 766–775.

Strozzi T., Wiesmann A., Kääb A., Joshi S. & Mool P. (2012) - *Glacial lake mapping with very high resolution satellite SAR data*. Natural Hazards and Earth System Sciences, 12, 2487-2498.

Tamburini A., Mortara G., Belotti M. & Federici P. (2003) - *The emergency caused by the "Short-lived lakes" of the Belvedere Glacier in the summer 2002 (Macugnaga, Monte Rosa, Italy). Studies, survey techniques and main results*. Terra glacialis VI, 51-54.

Tartari G, Salerno F., Buraschi E., Bruccoleri C. & Smiraglia C. (2008) - *Lake surface area variations in the North-Eastern sector of Sagarmatha National Park (Nepal) at the end of the 20th Century by comparison of historical maps*. Journal of Limnology, 67 (2), 139-154.

Terrier S., Jordan F., Schleiss A.J., Haeberli W., Huggel C. & Künzler M. (2011) - *Optimized and adapted hydropower management considering glacier shrinkage scenarios in the Swiss Alps*. In: Schleiss A., Boes R. M. (eds) Proceedings of the International Symposium on Dams and Reservoirs under Changing Challenges - 79th Annual Meeting of ICOLD, Swiss Committee on Dams, Lucerne, Switzerland Taylor & Francis Group, London, 497-508.

Tropeano D., Govi M., Mortara G., Turitto O., Sorzana P., Negrini G. & Arattano M. (1999) - *Lo svuotamento del Lago delle Locce in alta Valle Anzasca*. In: Eventi alluvionali e frane nell'Italia Settentrionale. Periodo 1975-1981. CNR-IRPI, Torino. 240-243.

Villa F., De Amicis M. & Maggi V. (2007) - *GIS analysis of Rutor glacier (Aosta Valley) volume and terminus variations*. Geografia Fisica e Dinamica Quaternaria, 30. 87-95.

Villa F., Tamburini A., Deamicis M., Sironi S., Maggi V., Rossi G. (2008) - *Volume decrease of Rutor Glacier (Western Italian Alps) since Little Ice Age: a quantitative approach combining GPR, GPS and cartography*. Geogr. Fis. Dinam. Quat., 31, 63-70.

Vincent C., Auclair S. & Le Meur E. (2010) - *Outburst flood hazard for glacier-dammed Lac de Rochemelon, France*. Journal of Glaciology, 56 (195), 91-100.

Wessels R., Kargel J. & Kieffer H. (2002) - *ASTER measurement of supraglacial lakes in the Mount Everest region of the Himalaya*. Annals of Glaciology, 34, 399-408.

Westoby M. J., Brasington J, Glasser N., Hambrey M., Reynolds J. & Hassan M. A.A M. (2014) - *Numerical modelling of Glacial Lake Outburst Floods using physically based dam-breach models*. Earth Surface Dynamics, 3, 171–199.

Williams R.S. & Ferrigno J.G. (eds.) (1993) - *Satellite image atlas of glaciers of the world: EUROPE*. US Geological Survey Professional Paper 1386-E-1, 48pp.

Worni R., Huggel C. & Stoffel M. (2013) - *Glacier lakes in the Indian Himalayas – From an area-wide glacial lake inventory to on-site and modeling based risk assessment of critical glacial lakes*. Science of the Total Environment, 468-469, s71-s84.

Zemp M., Frey H., Gärtner-Roer I., Nussbaumer S.U., Hoelzle M., Paul F., Haeberli W., Denzinger F., Ahlstrøm A.P., Anderson B., Bajracharya S., Baroni. C., Braun L.N., Ceres B.E.C., Casassa G., Cobos G., Vila R.R.D., Delgado Granados H., Demuth M.N., Espizua L., Fischer A., Fujita K., Gadek B., Ghazanfar A., Hagen J.O., Holmlund P., Karimi N., Li Zh., Pelto M., Pitte P., Popovnin V.V., Portocarrero C.A., Prinz R., Sangewar C.V., Severskiy I., Sigurđsson O., Soruco A., Usubaliev R. &Vincent C. (2015) - *Historically unprecedented global glacier decline in the early 21st century*. Journal of Glaciology 61 (228), 745-762.

Zemp M., Haeberli W., Hoelzle M. & Paul F. (2006) - *Alpine glaciers to disappear within decades?* Geophysical Research Letters, 33, L13504.

Zemp M., Paul F., Hoelzle M & Haeberli W. (2008) - *Glacier Fluctuations in the European Alps, 1850-2000: an overview and a spatiotemporal analysis of available data*. In: Orlove B., Wiegandt E. & Luckman

B. H. (Eds.), “Darkening Peaks: Glacier Retreat, Science, And Society”. University of California Press, Berkeley, CA, 152-167.

Zhang G., Yao T., Piao S., Bolch T., Xie H., Chen D., Gao Y., O’Reilly C. M., Shum C. K., Yang K., Yi S., Lei Y., Wang W., He Y., Shang K., Yang X. & Zhang H. (2016) - *Extensive and drastically different alpine lake changes on Asia’s high plateaus during the past four decades*. Geophysical Research Letters, 44, 9 pp.

Zhang G., Yao T., Xie H., Wang W. & Yang W. (2015) - *An inventory of glacial lakes in the Third Pole region and their changes in response to global warming*. Global and Planetary Change, 131, 148-157.

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