Socio-environmental value of glacier lakes: assessment in the Aosta Valley (Western Italian Alps)

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Corresponding Author:	CRISTINA VIANI, PhD Universita degli Studi di Torino Torino, Italy ITALY
Corresponding Author Secondary Information:	
Corresponding Author's Institution:	Universita degli Studi di Torino
Corresponding Author's Secondary Institution:	
First Author:	CRISTINA VIANI
First Author Secondary Information:	
Order of Authors:	CRISTINA VIANI
	Nicola Colombo
	Irene Maria Bollati
	Giovanni Mortara
	Luigi Perotti
	Marco Giardino
Order of Authors Secondary Information:	
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Viani Cristina[1*] cristina.viani@unito.it

Colombo Nicola[2] nicola.colombo@unito.it

Bollati Irene Maria[3] irene.bollati@unimi.it

Mortara Giovanni[4] giovanni.mortara@irpi.cnr.it

Perotti Luigi[1] luigi.perotti@unito.it

Giardino Marco[1] marco.giardino@unito.it

* Corresponding author

[1] Department of Earth Sciences, University of Torino, Via Valperga Caluso 35, 10125 Torino, Italy

[2] Department of Agricultural, Forest and Food Sciences, University of Torino, Largo Paolo Braccini 2, 10095 Grugliasco, Italy

[3] Earth Science Department "A. Desio", University La Statale of Milano, Via Luigi Mangiagalli 34, 20133 Milano, Italy

[4] Research Institute for Geo-Hydrological Protection, Italian National Research Council, Strada delle Cacce 73, 10135 Torino, Italy

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ABSTRACT

Progressive glacier retreat can deeply impact high-mountain areas. New glacier lakes are forming and potential connected opportunities (e.g. geosystem services) and risks (e.g. floods) are emerging. In the last decades, glacier lakes in the European Alps have increased in number and size, including in the study area (Aosta Valley Region, NW Alps, Italy). This work presents a methodology for a regional scale assessment of the potential of glacier lakes for socio-environmental development of mountain territories. Within the Aosta Valley, 337 glacier lakes were identified covering a total area of about 1.55 km^2. These lakes were numerically evaluated and ranked through a semi-automatic analysis in a GIS environment that was based on a set of parameters related to: 1) the geo-environmental value; 2) the existence of human infrastructures and/or activities close to the lakes; 3) the potential interaction of natural instabilities within the areas surrounding the lakes. Results showed the robustness of the assessment considering some of the highest scored lakes (e.g. Lago del Miage, lakes at the Rutor Glacier, etc.) and mountain sectors (Mont Blanc and Matterhorn areas). The application of the proposed methodology represents an initial step towards the identification of hot-spot lakes for a sustainable and integrated management, that also takes into account potential risk conditions connected to natural instabilities.

KEYWORDS: Glacier lakes; European Alps; Geosystem services; Sustainable management.

1 INTRODUCTION

Ongoing climate change is deeply impacting high-mountain areas, and glacier shrinkage is one of the most evident consequences. It is expected that the rapid retreat of glaciers, observed in the European Alps and other mountain regions of the world, will continue in the future (Zemp et al. 2006; Hock et al. 2019; Zekollari et al. 2019). The shrinkage and disappearance of glacier masses are producing substantial modifications in high-mountain environments: alpine geomorphological landscapes are evolving, and new landforms are developing along with new opportunities and risks (Diolaiuti and Smiraglia 2010). This calls for new methodologies for assessing geomorphic changes in glacial and periglacial areas (Bertotto et al. 2015). Among the newly formed landforms in recently deglaciated areas, there are overdeepenings and hollows that are occupied by glacier lakes when the conditions are favorable (Linsbauer et al. 2009; Buckel et al. 2018). Progressive glacier retreat is hence followed by an increased number of new glacier lakes (Paul et al. 2007; Carrivick and Tweed 2013; Mergili et al. 2013; Emmer at al. 2014; Salerno et al. 2014; Viani et al. 2016; Laute and Beylich 2021) and by a significant geomorphological evolution (disappearing, expansion/shrinkage) of the existing ones (Gardelle et al. 2011; Salerno et al. 2014, 2016; Zhang et al. 2017). Along with new lake formation, also the slopes in the deglaciated areas are undergoing changes, due to glacial dynamics that are gradually being substituted by gravity- and water-related processes (i.e. paraglacial dynamics; Ballantyne 2002). These processes can interact differently with lakes, potentially inducing hazardous situation (GAPHAZ 2017).

Among the most potentially hazardous situations there are the Glacial Lake Outburst Floods (GLOFs), which are characterized by a sudden release of water from a glacier lake (Westoby et al. 2014) and consequent powerful floods with high destructive potential and far-reaching impacts (Worni et al. 2013; Haeberli et al. 2017; Huggel et al. 2020). Among GLOFs conditioning factors, the most important are: triggering mechanisms (e.g. snow and/or ice avalanches, rockfalls, rapid input of water, etc.); reservoir hypsometry; geometry, composition, and structural integrity of the moraine dam (in case of moraine-dammed lakes); topography and geology of the flood path (Huggel et al. 2004; GAPHAZ

2017). The rapid input of large volumes of material results in the formation of a displacement wave of lake water which can overtop and successively breach the lake dam. Other process that can lead to dam overtopping/breaching are: high-intensity rainstorm or snowmelt event, that can progressively raise the lake level till the overtopping of the dam structure; piping; wastage of a buried ice-core or seismic ground shaking earthquakes with connected abrupt structural failure of the moraine dam.

The formation and successive evolution of glacier lakes due to glacier shrinkage has been well documented in the main high-mountain areas of the world by several studies analyzing multitemporal optical satellite images and/or aerial orthophotos (European Alps: Frey et al. 2010; Salerno et al. 2014; Emmer et al. 2015; Viani et al. 2016; Buckel et al. 2018; Himalaya: Salerno et al. 2012, 2016; Tibetan Plateau: Zhang et al. 2017; Andes: Drenkhan et al. 2018; Caucasus: Stokes et al. 2007). Moreover, the interest of the scientific community in glacier lakes in the last 10 years is also shown by the development and application of specific models based on morphological analysis of terrain information (Glacier Bed Topography - GlabTop approach), to predict the suitable locations of potential future lakes (Linsbauer et al. 2012, 2016; Colonia et al. 2017; Kapitsa et al. 2017; Magnin et al. 2020; Viani et al. 2020).

When new lakes are formed, opportunities and risks may arise (Haeberli et al. 2016). Glacier lakes contribute to the geodiversity of proglacial areas (Diolaiuti and Smiraglia 2010) and provide specific geosystem services (Gray 2013; Tognetto et al. 2021), both at the local and regional scale. Considering the 25 geosystem services described and classified in four groups by Gray (2013), those connected to glacier lakes can be distinguished as follows:

1) *regulating services*: atmospheric (hydrological cycle) and terrestrial processes (geomorphological processes may vary according to presence of lakes; e.g. Carrivick and Tweed 2013), which also have potential for flood and water quality regulation;

2) *supporting services*: the environmental relevance of glacier lakes is related to habitat provisioning contributing to high-mountain biodiversity (Čiamporová-Zaťovičová and Čiampor 2017; Tiberti et al.

2020); moreover, glacier lakes provide water as a platform for human activity and they are basins for water burial and storage;

3) *provisioning services*: lakes supply valuable material and immaterial goods for society; they are sources for hydropower production (Terrier et al. 2011; Purdie 2013), water reservoir (Drenkhan et al. 2019), and tourism attractions (Purdie 2013; Wang and Zhou 2019); these services can be interpreted as the economic value of glacier lakes;

4) *cultural services*: they concern the value that society gives to lakes in relation to their social meaning and to the importance for the community (e.g. environment quality, geotourism, cultural meaning, social development, research, education, and employment). Moreover, the cultural value of lakes also lays in their role in raising awareness about the potential hazards present in such environments (Allen et al. 2009; Worni et al. 2013; Emmer et al. 2015, 2016), which can hit people who are not properly informed (see the Lago del Miage wave in 1996 hitting people along its shore; Bollati et al. 2013).

Numerous are the studies on the hazards connected to the presence of glacier lakes, assessed mainly by remote sensing techniques, topographic and geomorphometric analysis, and modelling approaches (e.g. Huggel et al. 2002; Bolch et al. 2011; Mergili and Schneider 2011; Schaub et al. 2013; Nussbaumer et al. 2014, Westoby et al. 2014; Aggarwal et al. 2016; Cook et al. 2016; Emmer et al. 2020). On the other hand, there are few investigations on the services provided by glacier lakes (e.g. NELAK Project "New lakes in de-glaciating high-mountain areas: climate-related development and challenges for sustainable use" (Haeberli et al. 2013), with a particular focus on lake management considering future water shortages (Brunner et al. 2019; Drenkhan et al. 2019; Kellner and Brunner 2021).

The present work aims at proposing and applying a methodology to reveal the value of glacier lakes from a "human perspective", at the regional scale. Lake potentialities were assessed considering aspects that are important from the societal point of view and for the development of mountain territories. This first-order estimation is an essential basis for identifying potential "hot-spot lakes" as sites to prioritize for further detailed investigations aimed at their valorization, enjoyment, fruition, and towards their sustainable management from the socio-environmental point of view.

2 STUDY AREA

The Aosta Valley (Fig. 1) is a mountainous and rather small administrative region (3,262 km^2) located in the Western Alps of Italy. The number of inhabitants per km^2 is 39, with the population mainly concentrated in the valley bottom, reaching the highest density within the Aosta city (1,610 inhabitants per km^2) (year 2015, source: www.regione.vda.it, accessed on 21st June 2021). The service sector is responsible for around 80% of the regional GDP, with a very relevant role played by tourism (year 2020, source: www.bancaditalia.it, accessed on 21st June 2021). In the Aosta Valley, there are 184 hydropower plants capable of producing a total amount of ca. 1000 MW, corresponding to ca. 5% of the total hydroelectric power production in Italy (year 2019, sources: www.enelgreenpower.com, www.gse.it, accessed on 21st June 2021). The elevation ranges between 321 and 4808 m a.s.l., with more than 80% of the surface laying above 1500 m a.s.l. (D'Amico et al. 2020). It includes important glaciated massifs such as Gran Paradiso (4061 m a.s.l.), Mont Blanc (4808 m a.sl.), and Monte Rosa (4559 m a.s.l.). The Aosta Valley is the region with the most extensive glacier cover in Italy. According to the new Italian Glacier Inventory (Smiraglia et al. 2015), relative to the 2005–2011 period, in the Aosta Valley Region there are 192 glaciers with a cumulative area value of 133.7 km^2, which corresponds to 36% of the Italian glacier area. The glaciers cover an elevation ranging from about 1400 to 4800 m a.s.l. Considering the recent glacial withdrawal in Italy in the time period between 1959-1962 and 2005-2011, the Aosta Valley has given the largest contribution (-24% of its previous area) to the total national glacier loss (-30.5%) (Smiraglia et al. 2015).

Viani et al. (2016; 2018) reported the presence of ca. 170 glacier lakes and ponds in 2006-2007 within the Little Ice Age (LIA) glacier extent in the Aosta Valley, covering an area of about 1.2 km^2. Seven lakes with an area larger than 30,000 m^2 represented about 47% of the total lake coverage, but only 4% of the total number of lakes. On the other hand, lakes smaller than 6,000 m^2 accounted for 76% of the total number, but represented only the 20% of the total area. Finally, Viani et al. (2020) have modeled

46 potential overdeepenings (covering a total area of about 3 km^2) as potential sites suitable for future glacier lakes formation.

3 DATA AND METHODS

The overall methodological approach adopted in the present work and described in the following paragraphs is summarized in the flowchart in Fig. 2.

3.1 Glacier lake inventory update with respect to 2006-2007 previous inventory

High-resolution aerial orthophotos were proven to be important data sources for glaciological purposes (Lucchesi et al. 2013; Salvatore et al. 2015; Smiraglia et al. 2015). The Aosta Valley Region and the National Agricultural Information System Agency (AGEA) performed a photogrammetric flight in 2015, and the final digital orthophotos (with a spatial resolution of 0.2 m) were used as base layers in an open source Geographic Information System (GIS) environment (Q-gis® 3.16). Glacier lakes with a surface area greater than 100 m^2 were detected and their outlines were manually digitized in GIS environment. The extensions of the LIA glaciers produced in the framework of the GlaRiskAlp project were used as polygons in which detecting the lakes. The extensions are available as. kml file from the project website (http://www.glariskalp.eu/?it_inventario-delle-estensioni-attuali-e-passate-dei-ghiacciai,9, accessed on 14th April 2021; Lucchesi et al. 2014).

The area and elevation of each lake were calculated. Regarding the accuracy of the derived data (total area covered by lakes), the approach adopted by Viani et al. (2016) based on previous studies by Citterio et al. (2007) and Minora et al. (2016) was applied. This approach considers the linear resolution error (LRE) and it is based on the assumption that the image resolution influences the accuracy of lake mapping. The area precision for each lake was evaluated by buffering the lake perimeter, considering the area uncertainty. The LRE should be half the resolution of the image pixel, in the present case 0.1 m. The precision of the whole lake coverage was estimated as the root squared sum (RSS) of the buffer areas.

Furthermore, every lake was classified according to the type of dam as: bedrock-dammed, moraine-dammed, and ice-dammed. The type of impounding was assigned by visual interpretation of aerial orthophotos and/or high-resolution hillshade of the lake surroundings (Lucchesi et al. 2019). Finally, each lake was associated to the corresponding mountain sectors, with Italian names accordingly to the Alpine supergroups of the International Standardized Mountain Subdivision of the Alps (ISMSA-SOUISA; Marazzi 2005). Glacier areas of the 2006-07 snapshot by Salvatore et al. (2015) were also updated at 2015 by identification and manual digitalization of glacier outline on the same aerial orthophotos used for the lake inventory. The update was performed in order to obtain the total surface variation of glaciers in the considered period and compare it with the lake area variation.

3.2 Assessment of the socio-environmental value of glacier lakes at the regional scale

According to the geosystem services provided by the lakes (i.e. regulating, supporting, provisioning, and cultural), it is possible to infer their socio-environmental value. The proposed semi-quantitative assessment was designed by choosing parameters that allowed revealing the geosystem services potentially provided by the lakes, focusing on those important from the societal point of view and for the development of mountain territories. Then, selected parameters were grouped in three main categories related to the following aspects: geo-environmental value, interaction with human activities and usages, and interaction with natural instabilities. Information about the interaction of the lakes and surrounding areas with natural instabilities provides a rationale for excluding sites in relation to potential risk conditions and, in turn, selecting those that provide benefits without risks.

The present approach (Tab. 1) was also implemented following the methodology proposed by Bollati et al. (2013; 2017 and supplementary material therein). By working at the hydrographic basin scale and combining field surveys and remote sensing analyses, Bollati et al. (2013; 2017) aimed at: 1) identifying potential geomorphosites; 2) evaluating these sites by applying a series of numerical criteria (scientific value, additional values and potential for use, scientific index and educational index); 3) selecting the most suitable geomorphosites according to different purposes (scientific research, education, and touristic exploitation). In Bollati et al. (2013), glacier lakes were assessed as potential geomorphosites. However, the method proposed by the authors could not be applied without modifications into a regional-scale study, since on-field surveys are not always possible and a more automatized procedure is then required. The methodology proposed here is semi-automatic and it includes some parameters detected by the operator (i.e. *Geomorphological features evidence*), and other ones extracted automatically from existing vector files (i.e. instabilities and avalanches inventories) and rasters (i.e. Digital Terrain Model, DTM).

In order to rank the lakes, a numerical evaluation was designed starting from a selection of the parameters adopted in the mentioned methodologies, in some case adapting them to the specific case of glacier lakes, and including novel parameters. In order to minimize the problem of subjectivity, it was crucial to assign numerical values corresponding to particular categories for each selection parameter during the evaluation phase. Each parameter had a score between 0 and 1 (indicated in brackets in the following paragraphs), but the ranges were different depending on the number of possible alternative choices. In table 1 the summary of all the assessed features is reported. The summary is grouped in three main categories: *geo-environmental value*, *interaction with human activities and usages,* and *interaction with natural instabilities*.

The assessment was supported by the creation of different buffers for each lake. Four buffer areas were created for each lake: 1 km, 2.5 km, 5 km, and 10 km (from the lake perimeter). Buffers were additionally clipped with the main hydrographic catchment (main valley) of the Aosta Valley Region to which the lake belong in order to avoid the inclusion of portions of adjacent valleys. The first evaluation occurred at single lake level, then, the obtained values were elaborated at the level of mountain sector.

3.2.1 Data sets and sources

In Tab. 1, the datasets and sources used for the evaluation of lakes are listed. Hereafter each dataset/source is described in detail providing the related metadata information.

Orthophotos - The digital orthophotos obtained from the photogrammetric flight performed in 2015 by the Aosta Valley Region and the AGEA were used. The spatial resolution is 0.2 m.

High-resolution hillshade - A hillshade is a grayscale 3D representation of the surface, with the sun relative position taken into account for shading the image. It was obtained in GIS environment (Q-gis® 3.16) with the related raster function from the LIDAR-derived DTM acquired in 2008 and with a spatial resolution of 2 m.

Geological map and related structural elements - The map, at the 1:100,000 scale, was prepared and revised by the Aosta Valley Region in 2005 as part of the "Progetto CARtografia Geologica" (CARG), a project for national geological cartography. Structural elements are represented by lines in a dedicated shape file available on the Geonavigator of the Aosta Valley Region (http://geologiavda.partout.it/GeologiaVDA/default/GeoCartaGeo, accessed on 14th April 2021).

Lake inventory - The most updated glacier lake inventory, produced in the present research.

LIA glacier extent - Polygonal shape file representing the glacier extent in 1850 available as .kml file (http://www.glariskalp.eu/?it_inventario-delle-estensioni-attuali-e-passate-dei-ghiacciai,9 - accessed on 14th April 2021).

Territorial Landscape Plan of the Aosta Valley Region - It is an instrument for the governance and planning of the regional territory. It was approved in 1998 and it aims at directing and coordinating the actions of the public administration focusing on environmental aspects and protection of the territory. It consists of texts, sheets, and maps with related downloadable shape files. Vector files are available on the Geoportal of the Aosta Valley Region (https://geoportale.regione.vda.it/download/ptp/, accessed on 14th April 2021).

Open Street Map - The OpenStreetMap project provides increasingly extensive map data for the entire world. The map is available as Quick Map Service plug-in in Q-gis® 3.16.

Web Map Service (WMS) of protected areas - The map highlights parks, natural reserves, and areas belonging to the Natura 2000 Ecological Network and the habitats present on the regional territory. It was published in 2016 and is available as WMS (https://geoportale.regione.vda.it/wms/, accessed on 14th April 2021).

DTM - It is a LIDAR-derived DTM acquired in 2008 with a spatial resolution of 2 m.

Regional avalanche inventory - It is available as a webGIS and reports the areas covered by avalanches identified in the period 2005-2020 (https://mappe.partout.it/pub/geovalanghe/, accessed on 14th April 2021).

Italian Landslide Inventory (IFFI) - The inventory, available as shape files (https://idrogeo.isprambiente.it/app/page/open-data, accessed on 14th April 2021), is updated to 2016 for the Aosta Valley Region. Each landslide is represented by a point located at the landslide crown, by a polygon when the surface of the landslide can be mapped at the adopted survey scale (from 1:10,000 to 1:25,000), or by a line when the width of the landslide cannot be mapped (e.g. rapid debris flows).

3.2.2 Geo-environmental value

The geo-environmental value category includes the analysis of geomorphological, geological, and hydrological features characterizing the lakes. It aims at revealing lakes whose peculiarities are of potential interest for the scientific community, either in term of environmental interpretation or monitoring, but also for other purposes such as preservation actions of bio and/or geodiversity, educational activities, etc., thus providing supporting and cultural geosystem services.

Geomorphological features evidence (i.e. modified from *representativeness of geomorphological and paleogeomorphological processes* in the *Scientific Value*; Bollati et al. 2017*)* - Geomorphological features may influence lake existence and evolution, in particular the characteristics of the landform impounding the lake (i.e. dam type). Lakes were distinguished in two classes depending on the presence (or absence) of evident geomorphological features impounding the lake. The assignment was based on the information about the dam type included in the glacier lake inventory and by additional investigation of the lake surroundings by visual interpretation of aerial orthophotos and/or high-resolution hillshade. Presence of evident geomorphological features (1) implies impounding by lateral/frontal moraine, overdeepened bedrock, or ice. Absence of evident geomorphological features (0) corresponds to a non-specific impounding (e.g. basal till, fractured bedrock). This attribute is used to stress the relation between lake existence and evolution and geomorphological processes.

Structural features evidence (i.e. modified from *representativeness of geological processes* in the *Scientific Value*; Bollati et al. 2017) - Structural constraints may influence lake existence and evolution, such as various scale faults and other tectonic lineaments by controlling bedrock resistance, hydrogeological properties, and local response to geomorphic processes (Ollier 1981; Silva et al. 2003; Goldrick and Bishop 2007). Major regional structural features in vector format were buffered for 500 meters. The presence or absence of glacier lakes in the buffered areas were investigated in order to define the two classes: lakes located within areas crossed by structural features (1) and lakes not located within areas crossed by structural features (0). This attribute is used to stress the relation between surface modeling and bedrock features.

Hydrological complexity (i.e. modified and adapted from *geodiversity* in the *Scientific Value*; Bollati et al. 2017) - Complexes of several lakes in the same deglaciated area can be considered an additional environmental value. In other words, increasing values were given to single lakes presenting one or more additional lakes within the related LIA glacier extent. Indeed, the hydrological complexity was considered from a twofold point of view: landscape ecology and geodiversity. On the one hand, reduced distance among multiple lakes and ponds within the catchment can increase the connectivity (e.g. Gould et al. 2012). Connectivity can influence gene flow, recolonization potential, and resistance to biological invasions of metapopulations of aquatic and semi-aquatic species, such as amphibians, in high-mountain aquatic habitats (e.g. Murphy et al. 2010; Tiberti 2018). On the other hand, the compresence of multiple and newly generated geomorphosites (i.e. lakes) in the same deglaciated area entails an increase of geodiversity (Diolaiuti and Smiraglia, 2010). Three classes were defined: single lake located within the LIA extent of the related glacier (0); two lakes within the LIA extent (0.5); complex of more than two lakes within the LIA extent (1).

3.2.3 Interaction with human activities and usages

The present category includes the analysis of the occurrence, and thus the potential interaction, of different human infrastructures and/or activities within the territory where the lake is located. It is intended to identify the lakes that could be of potential interest for the implementation of human activities, in particular for possible connected regulating, supporting and, provisioning geosystem services.

Human settlement presence (i.e. modified from *Services* in the *Potential for Use*; Bollati et al. 2017) - The presence of human settlements was analyzed in 2.5 (1), 5 (0.67), 10 km (0.33), and above 10 km (0) from the lake.

Spatial accessibility (i.e. modified from *Spatial accessibility* in the *Potential for Use*; Bollati et al. 2017) - The modality to access the 1 km buffer area of the lake was investigated. In particular, the following possibilities to reach the lake were considered, from the less to the most favorable: not accessible (0); accessible by foot on alpinist paths (0.25); accessible by foot on excursionist paths (0.5); accessible by dirt roads or cable ways (0.75); accessible by paved roads (1).

Socio-economic value (i.e. modified from *Socio-economic value* in the *Additional Value*; Bollati et al. 2017) - The presence of socio-economic elements such as ski areas, ski lifts, cable ways, dams, mountain huts, bivouacs, and pastures within 1 (1), 2.5 (0.67), 5 (0.33), and over 5 km (0) from the glacier lakes was also taken into account. In particular, the mentioned elements were selected because connected to human activities that could benefit from the presence of glacier lakes as water reservoir.

Lake area (i.e. modified and adapted from *Aesthetic value* in the *Additional Value*; Bollati et al. 2017)- The lake area was calculated and classified in three different classes, according to the natural breaks method (Jenks 1967). Class breaks are created for best grouping similar values and maximizing the differences between classes. Natural breaks are data-specific classifications. It is intended that the larger is the lake (above ca. 30,000 m^2 in the case of the lakes considered in the present study) the higher is its value for human activities (e.g. water reservoir, hydropower production, flood retention; and tourism in term of lake aesthetic value).

Legal constraints (i.e. modified from *Legal constraints* in the *Potential for Use*; Bollati et al. 2017) - A potential obstacle for lake fruition for human activities could be its inclusion in a protected area. Lakes were differentiated between two groups according to the presence (0) or not (1) of protection measures.

3.2.4 Interaction with natural instabilities

This category includes the analysis of the presence, and thus the potential interaction, of various natural instabilities within the territory where the lake is located and of the potential of the lake itself to generate hazardous conditions (i.e. GLOF). Bollati et al. (2017) considered natural hazards using a qualitative approach, here a quantitative value is given. Natural instabilities are a limit to the potential development of lakes, generating potential risk conditions due to the interaction with human infrastructures. Thus, the present category is intended to provide a rationale for cautious management of lakes with high socio-environmental value (emerging from the two previous categories) in relation to potential risk conditions.

Energy relief - Energy relief (Zwoliński 2008; 2009) shows the diversity of relative (local) heights and thus reveals the topographic diversity of the area. Mean energy relief was calculated from the LIDAR DTM of the Aosta Valley Region in the buffer area of 1 km from the lake perimeter and classified by the natural breaks method (Jenks 1967). Energy relief gives information about areas more prone to gravity-related instabilities.

Snow and ice avalanches - The presence (1) or absence (0) of snow and ice avalanches in the buffer area of 1 km from the lake perimeter was investigated. Moreover, the interaction of snow and ice avalanches with accessibility features and infrastructures (e.g. paths, dirt roads, cable cars, and ski lifts) reaching the lake was also taken into account.

Landslides - The presence (1) or absence (0) of landslides in the buffer area of 1 km from the lake perimeter was investigated. Moreover, the interaction of slope instabilities with accessibility features and infrastructures reaching the lake was also taken into account.

GLOF - Glacier Lake Outburst Flood - Interaction of GLOF path and run-out area with human infrastructures as foot paths, huts, ski lifts and cable ways, ski areas, human settlements, and main roads was investigated. GLOF path and run-out area were modelled following the *Gravitational Process Path Model* (GPP model) by Wichmann (2017). The GPP model simulates gravitational processes and, in particular, the movement of a mass point from an initiation site to the deposition area. It is a GIS-based flow-routing algorithms that can be included in the category of the simplest computational models transferring flow of gravitational processes (included GLOF) sequentially downslope across a digital terrain model. The model is based, as Modified single-flow (MSF) models adopted for GLOF simulation (Huggel et al. 2002, 2003; Allen et al. 2009), on one of the earliest, simplest, and most frequently used routing method for specifying flow directions (the “D8” method introduced by O'Callaghan and Mark 1984). They are relatively simple, computationally-undemanding, purely raster- and DTM-based approaches for modelling downstream propagation of geomorphological processes including GLOFs and are suitable for regional scale studies. The GPP model integrates components for process path determination, run-out calculation, sink filling, and material deposition. Information about the initiation sites organized in so-called release areas, represented by one or more grid cells labeled as starting zones and a digital terrain model (DTM) is required as input data. In the present study the starting zones are represented by raster data set derived from lake areas, while the DTM used is the 2008 LIDAR DTM of the Aosta Valley Region.

3.2.5 Calculation and spatial analysis

The scores obtained by assessing each lake according to the single parameter in the three main categories were used for detailed calculations provided in Tab. 2. Calculations were first performed at the single lake scale. Then, the results were grouped and averaged according to mountain sectors to which single lakes belong. A spatial analysis was also performed in order to determine the most suitable lakes and/or mountain sectors in relation to the specific categories (e.g. geo-environmental value), or even individual attributes (e.g. socio-economic value).

4 RESULTS AND DISCUSSION

4.1 2015 glacier lake inventory and recent evolution of lake population

In this study, 337 glacier lakes were identified, with a total area of 155.15 (±0.82) × 10^4 m^2 (median 0.46 × 10^4 m^2). Lakes areas varied between a minimum of about 0.01 × 10^4 m^2 to a maximum of 12 × 10^4 m^2. Approximately 67% of the lakes were characterized by an area smaller than 0.2 × 10^4 m^2 and 84% of the lakes had a surface area less than 0.6 × 10^4 m^2. The elevation ranged between 1820 and 3382 m a.s.l. (mean value: 2800 m a.s.l.). In the year 2015, 70% of the lakes were located between 2600 and 3000 m a.s.l. According to mountain sectors (Fig. 1), glacier lakes of the 2015 inventory were localized mainly in the Rutor-Lechaud (30%), Gran Sassière-Tsanteleina (16%), Bouquetins-Cervino (12%), and Monte Rosa (12%). The geographic distribution of the glacier lakes was similar to those of the 2006-2007 inventory for the first two most lake-populated mountain sectors that were followed in the previous inventory by the Monte Rosa and the Gran Paradiso. They were mainly proglacial lakes impounded by bedrock (fractured bedrock - 32% or evident bedrock overdeepenings - 12%), basal debris (41%), or moraine (11%). There were also a few cases of ice-dammed lakes (4%). As mentioned in similar studies (e.g. Emmer et al. 2020), also for the Aosta Valley glacier lakes there is the evidence of a transition from moraine-dammed lakes (dammed by the LIA moraines) already existing in the oldest inventories (Viani et al. 2016; 2018), to bedrock-dammed lakes (impounded by fractured bedrock or by bedrock overdeepenings). This last type of lake is becoming predominant, including also lakes impounded by basal debris potentially covering a bedrock dam.

With respect to the last complete inventory related to 2006-2007 (Viani et al. 2016; 2018), until 2015 (Tab. 3):

- the total number of lakes doubled (about 19 lakes formed per year);

- the total area increased of ca. 30% (with an annual rate of ca. 0.04 km^2/yr of new lake area);

- the mean elevation raised because of new lakes in recently deglaciated areas left by glaciers at progressively higher elevation;

- the mean area decreased because of a large amount of newly formed small lakes in areas recently exposed by small ice body (<0.5 km^2) that are predominant (ca. 84%). Moreover, according to the type of classification, the majority are mountain glaciers and glacierets (according to Smiraglia et al. 2015), which are not characterized by large tongues with thick ice, that are the conditions for the presence of large overdeepenings;

- glaciers lost 3% of their surface.

Considering the number of new lakes per year, a similar result (19 lakes/yr) has been shown by Mölg et al. (2021) in Switzerland, for a comparable time period (2006-2015). The calculated new annual lake area was about the quadruple (0.15 km^2/yr) with respect to the Aosta Valley. In Austria, Buckel et al. (2018) found a lower number of lakes per year (6.5), although the new annual lake area was double (0.08km^2/yr) with respect to the present study. Considering the mean elevation of glacier lakes, the value found in the Aosta Valley (2800 m a.s.l.) was higher with respect to both Switzerland and Austria, which showed similar elevations (ca. 2600 m a.s.l.).

The increase in lake number and area that has occurred in the most recent decade (from 2006 to 2015) is the strongest, considering the entire XX and beginning of XXI centuries (Viani et al. 2016). Similar results emerged from Mölg et al. (2021), who found an exceptionally strong increase of glacier lakes from 2006 to 2016 in Switzerland. Similarly, a sudden increase in lake number and area over the most recent decade (2006-2015 period) was found by Buckel et al. (2018) in Austria.

Considering the exposed area due to glacier retreat since the Little Ice Age (193 km^2) with respect to the total area covered by glacier lakes in 2015 (1.55 km^2), 0.8% of the deglaciated area was occupied by lakes. A similar result, ca. 0.9%, was found by Mölg et al. (2021) in Switzerland (deglaciated area: 740 km^2 of deglaciated area; area occupied by lakes: 6.22 km^2) while, in Austria, Buckel et al. (2018) showed a lower percentage of ca. 0.5% (deglaciated area: 613 km^2; area occupied by lakes: 2.93 km^2).

4.2 Single lake assessment

In Fig. 3 the results of the assessment of the single glacier lakes of the Aosta Valley Region are presented. As suggested by Bollati et al. (2017), starting from the dataset of the potential geomorphosites (all the lakes, in this case), it is better to focus the discussion on a selection of lakes that have shown the highest indexed values with respect to the average values of all 337 lakes (Fig. 4). The discussed scores are related to the indexed single lake values that vary from a minimum of 0 to a maximum of 1.

Lakes that obtained the highest scores, considering the three aspects separately, are presented and discussed below. These are the most interesting results in the present research, especially in view of the identification of hot-spot lakes that can be managed for particular purposes regarding a specific category, such as scientific research or educational activities (geo-environmental value), exploitation for hydropower or snow production (human activities category), and risk mitigation (natural instabilities category).

4.2.1 Geo-environmental value

Considering single lakes, 34 of them obtained the maximum score (1) for the indexed geo-environmental value. One of them is the lake at the Tzére Glacier; it is a large lake of about 65,000 m^2 located in an evident bedrock overdeepening and it is connected to other glacier lakes in the related glacial basin (Fig. 5a). The formation and evolution through time of the lake at the Tzére Glacier (Monte Rosa, Ayas Valley) was analysed by Viani et al. (2016). Moreover, there is the Lago Goletta located in the proglacial area of the homonymous glacier (Gran Sassière-Tsanteleina, Rhêmes Valley). As the previous one, it is a very large lake of about 95,000 m^2 impounded by a bedrock overdeepening. The last lake formed in the recently deglaciated area of the Indren Glacier (Monte Rosa, Lys Valley), located in an overdeepened bedrock depression, has also obtained the highest score. The Indren Glacier lakes were studied from a hydrochemical point of view by Colombo et al. (2019a) and Vione et al. (2021). These lakes were also included in a wider lake population, with the neighboring lakes of the Long-Term Ecological Research Network (LTER), in order to understand the contribution of the glacier melt water to the chemical composition of the water of the lakes, compared to lakes that are not fed by glaciers (Colombo et al. 2019b). A high score was obtained also by the Lago del Miage. The Lago del Miage (Monte Bianco, Veny Valley) is of considerable significance for both scientific and touristic interest (Deline et al. 2004; Diolaiuti et al. 2006, 2017; Bollati et al. 2013, 2015). The lake has existed since the XVIII century. Deline et al. (2004) reported that several drainage events took place between 1930 and 1990. In particular, the authors analyzed the event occurred in September 2004, when the lake area was 36,000 m^2 and the depth was 30 m. Diolaiuti et al. (2006) described rates, processes, and morphology of freshwater calving at Miage Glacier into the Lago del Miage. Finally, the lakes at Balanselmo, Dragone and South-West Château des Dames glaciers (Bouquetins-Cervino, Valtournenche Valley) are worth mentioning. These lakes are located in evident bedrock overdeepenings, connected to each other, and influenced by the presence of structural features crossing the area from SW to NE (Fig. 5b).

4.2.2 Interaction with human activities and usages

The highest score (0.9) related to the presence of human activities in its proximity was achieved by the first formed lake in the proglacial area of the Rutor Glacier after the end of the LIA (Rutor-Lechaud, La Thuile Valley). The Lago del Rutor (Fig. 5c) is the third largest lake in the Aosta Valley in terms of lake area (ca. 103,000 m^2). It is located in a highly frequented area that is reached by an important excursionist path (Alta Via n. 2) and logistically supported by the presence of the Deffeyes Hut.

The second lake (score: 0.83) is the Gran Lago (previously mentioned for its high LGEV score). The lake is located at the South-West Château des Dames Glacier and it covers about 61,000 m^2 (Bouquetins-Cervino, Valtournenche Valley). The lake presents an artificial dam on the south side and, according to the Aosta Valley lake inventory, part of the water of the outflow is collected by a pipe.

The third ranking lake (score: 0.82) is one of the Cime Bianche lakes located in the proglacial area of the Valtournenche Glacier (Bouquetins-Cervino, Valtournenche Valley), with an extent of about 107,000 m^2 (Fig. 5d). Its outflow is partially channeled because of the presence of a dirt road crossing the drain path. The area presents several infrastructures, including artificial dams connected to ski activities.

4.2.3 Interaction with natural instabilities

This category represents a limit to the potentialities of lakes related to possible risk conditions (Haeberli et al. 2017).

The Eastern Morion Glacier (Rutor-Lechaud, Valgrisenche Valley) presents several moraine-dammed lakes positioned on a rocky step. The lakes show different colors on the aerial orthophotos and the 3D images from Google Earth; this is probably due to the different sources of the water filling them (melted glacier ice or precipitation). Marcello and Meda (2013) reported "water drainage and water channeling that overflowed the Lakes of Morion, forming waterfalls". These characteristics granted them a high geo-environmental value (1). Moreover, the presence in their proximity of the Angeli di Morion Hut and the passage of the Alta Via n. 2, one of the most famous excursionist routes in the Aosta Valley Region, also gave them a high value connected to the presence of human activities (0.7). The same lakes reached the highest scores (above 0.8) with respect to the presence of different potential instabilities affecting the area, in particular the sinking phenomena affecting the paths reaching the lakes. Moreover, the GLOF model shows that the area affected by a potential outburst flood could interact with the paths and the paved road in the main valley, generating potential risk conditions (Fig. 5e).

High value (0.92) connected to the presence of potential instabilities was found for the lake at the Frebouzie Glacier (Monte Bianco, Veny Valley). In fact, in 2002 the Frebouzie Glacier was affected by an ice avalanche detached from the glacier front, falling for about 400 m on the steep rock step (Deline et al. 2002; 2004. Fig. 5f). This has to be taken into account, especially now, given the presence of the lake.

4.3 Mountain sector assessment

The analysis performed on single lakes can also be applied aggregating the lakes according to the main mountain sectors of the Aosta Valley Region. The indexed mountain sector values (Fig. 6), ranging from 0 to 1 highlights the different performance of the lakes of the different mountain sectors.

Considering the geo-environmental value, the mountain sector showing the highest score is the Mont Blanc (0.77). This sector has fewer lakes (18) than the other ones in the region, although it includes the majority of the ice-dammed lakes in the study area (8), those located on the surface of the debris-covered Miage Glacier, and the well-known and well-studied Lago del Miage and Lago del Giardino del Miage (cf. Bollati et al. 2013; 2015). Moreover, values above the mean were observed for the two neighboring mountain sectors Luseney-Cian (0.71) and Bouquetins-Cervino (0.58). Indeed, they include the above-mentioned lakes at Balanselmo, Dragone, and South-West Château des Dames glaciers (Valtournenche Valley); these lakes are located in evident bedrock overdeepenings, connected to each other, and influenced by the presence of structural features crossing the area from SW to NE. The numerous lakes in the Breuil basin above the hamlet of Breuil-Cervinia are also included. According to these peculiar characteristics, they could be of interest for the scientific community focusing on the causes of the formation of glacier lakes and, more in general, on the emerging landforms in enlarging proglacial areas.

The mountain sector that shows the highest score related to the presence of glacier lakes (e.g. those in the proglacial area of the Valtournenche Glacier) close to human activities is the Bouquetins-Cervino (0.59). Bouquetins-Cervino is the third mountain sectors considering the number of glacier lakes (40) and it has important tourist centers like Breuil-Cervinia, ski resorts as well as artificial dams used for hydropower and snow production.

Regarding potential interactions of natural instabilities with the lakes and the surrounding areas, the mountain sector with the highest score is the Mont Blanc (0.62). This sector includes the above mentioned Frebouzie Glacier as well as the Triolet Glacier. The latter was affected in 1717 by a historical collapse of rock and ice that moved down the valley for about 7 kilometers (Porter and Orombelli 1980). Moreover, slopes of this sector are characterized by a high energy relief that can influence the activation and/or propagation of natural instabilities like outburst floods from glacier lakes. In fact, the GLOF modeled in the present study shows the flood path potentially reaching the valley bottom where a dirt road and an excursionist path are present.

4.4 Advantages, limits, and possible implementations of the applied methodology

4.4.1 Advantages

The present study aimed at identifying (by updating the glacier lake inventory) and selecting (by the application of the approach for lake socio-environmental value assessment) sites to be prioritized for valorization, enjoyment, fruition, and sustainable management from a socio-environmental point of view. The selection of elements was based on a numerical assessment including several parameters to which different scores were assigned to decrease the subjectivity associated with any evaluation procedure, as recommended for geosites (i.e. lakes) (Brilha, 2016). Following Brilha (2016), the assessment was performed at the regional scale and on dozens of sites for which the assessment reasonably provides more robust results than for a limited area and reduced number of sites. Moreover, Bruschi et al. (2011) showed that a high number of criteria does not necessarily imply a more accurate assessment, thus the selection was done according to the most representative ones for each of the three categories. Finally, a concluding reflection on the quality of the numerical results is essential by experts adopting the present approach. It has to be based on the knowledge of the context acquired directly by field surveys and indirectly by existing literature, in order to confirm the results and search for eventual invalid ranking positions (Brilha 2016). The subjectivity inherent to an assessment of geosites cannot be totally eliminated. However, the approach proposed in the present study can surely decrease some of this subjectivity that, in any case, is considered secondary with respect to the primary need of obtaining a sorted list of sites on which basing potential future management strategies.

The robustness of the results obtained from the application of the proposed methodology is confirmed by the fact that the value of several high-scored lakes has already been recognized by society. For instance, numerous lakes showing high geo-environmental values are already known among the scientific community and have been the subject of several studies (e.g. lakes at Tzére, Indren, and Miage glaciers). Moreover, some of the lakes with high values, according to the interaction with human activities and usages, are well established tourist destinations (e.g. Lago del Miage and lakes at the Rutor Glacier). Thanks to the results of this assessment, some highly interesting cases emerged from lakes that are not well known, and could be studied. For instance, the lakes at the Balanselmo, Dragone, and South-West Château des Dames glaciers, where a complex of geological and geomorphological features interact and influence lake conformation and position, are an ideal didactic example of high-mountain geodiversity.

4.4.2 Limits

The limits of this approach are linked to its presuppositions. Indeed, the method is designed in order to be semi-automatic and applicable at the regional scale. Some aspects like the potential ecologic support role of the lakes, as well as their cultural value, emerged as important characteristics that require deep consideration. They are fundamental geosystem services, however, despite their importance, they are difficult to be evaluated without an extensive survey. For example, the previously mentioned Lago Goletta, which shows a high geo-environmental value, was analysed by Tiberti et al. (2020), who recognized its ecological value related to the biotic main features (i.e. picocyanobacterial abundance). This characteristic was assessed as ecological support role in the scientific value frame for geomorphosites by Bollati et al. (2013; 2017), and it falls into the supporting geosystem service as proposed by Gray (2013). It is considered fundamental to assess a geomorphosite (Bollati et al. 2015), but this requires detailed case-by-case evaluation, which is not feasible at the regional scale. An attempt to partially consider the importance of lakes for the natural ecosystem is represented by the “Hydrological complexity” parameter although a further implementation is recommended.

Another example of characteristics that require deep consideration is represented by the lakes in the area of the Rutor Glacier. The area includes the Lago Santa Margherita (a lake outside the LIA glacier extent and thus not considered in the inventory and in the assessment). This lake is famous for the several GLOFs occurred between 1430 AD and 1864 AD due to glacier front fluctuations that caused much damage and many fatalities (Dutto and Mortara 1992; Orombelli 2005). Due to these events, religious processions were made to the area; later, in 1937, a chapel was built on a promontory on the lake as a devotional place to bring an end to the devastating outburst floods, and every year a Mass is celebrated. This aspect could be assessed as a cultural value of geomorphosites (Bollati et al. 2017), that considers the material and immaterial traditions linked to the site, and it is part of the cultural geosystem service proposed by Gray (2013). The cultural value was not considered in the present study since the proposed methodology needs a complete regional database of the analyzed parameters that is not available for cultural elements, as well as for the ecological value. These two aspects, in fact, assume a deep knowledge of the single lakes and of their related territory. Potentially, they could be evaluated for the high-scored lakes, with ad-hoc field surveys that could be conducted to collect further data.

The newly formed lakes are appearing and changing continuously, hence this relatively fast running and semi-automatic procedure could represent an ideal tool available to local administrators for periodic review of the status of glacier lakes, and of their value. A change in their conditions, for both natural or human-induced causes, can mine their values (Pelfini and Bollati 2014) and influence also the geodiversity of such dynamic contexts (Zwolinski 2009). The re-run of such analysis will be possible if the input data are periodically updated, especially the glacier lake inventories (derived from aerial orthophotos). Considering the other input data, it has to be taken into account that some of them may be outdated. In the present study, information sought from the Territorial Landscape Plan of the Aosta

Valley Region was used. It consists of texts, sheets, and maps with related downloadable shape files related to the situation in 1998 without subsequent updates. This is a limit to the use of the dataset because of important modification that can have taken place in the meantime on the regional territory. However, this is the only official information regarding human infrastructures and settlements. Updated information can be sought via OpenStreetMap that provides downloadable shapefiles. In this case, being the information of OpenStreetMap based on the concept of Volunteered Geographic Information (VGI), the data quality depends on the balance between contributors' freedom and their respect of specifications (Girres and Touya 2010). The outdated but officially approved information provided by the Territorial Landscape Plan of the Aosta Valley can be verified and integrated by the updated but heterogeneous data of OpenStreetMap.

Considering the choice of the GLOF path modelling, given the regional scale and main focus of the present study, a simple and computationally-undemanding model was chosen in order to have a first overview on GLOF path and run-out areas. This was necessary to understand the GLOF interactions with other lakes and human infrastructures. It is based, as models adopted for GLOF simulation (Huggel et al. 2002, 2003; Allen et al. 2009), on the same routing method for specifying flow directions (O'Callaghan and Mark 1984). Being a purely raster- and DTM-based approach, the input data needed are limited (lake area and DTM) and no additional information is required. There are also several established more sophisticated numerical GLOF modelling approaches that also consider dam type dependent outburst mechanisms or the hydrodynamic properties of the subsequent flood (e.g. Carrivick 2010; Westoby et al. 2015). They were used in specific studies on GLOF assessments (Westoby et al. 2014 and references therein), although they were not considered in the present approach because of their physical complexity and detailed input data required.

4.4.3 Potential implementations

The methodology proposed in the present study aims at considering and integrating different aspects that characterize glacier lakes. The goal of the present approach is not to propose specific methods for the elaboration of single parameters needed for the assessment. Indeed, if dedicated researches already exist on specific features, their results could merge into this comprehensive analysis, also extending its application to other mountain regions. This is particularly evident for studies on regional GLOF assessments that cover the main mountain regions of the world (e.g. Allen et al. 2019; Emmer et al. 2020). Finally, since there are inventories of potential future lakes in several mountain areas of the world (e.g. Magnin et al. 2020; Viani et al. 2020), it would be interesting to investigate the potential of future lakes as sources of geosystem services for society.

The application of the proposed methodology represents an initial step towards the identification of hot-spot lakes to be sustainably managed for a number of purposes like geoscience education, landscape protection, nature conservation, tourism attraction, hazard mitigation, water reservoir for mountain huts, and artificial snow and/or hydropower production. The mentioned purposes can be in synergy and/or in conflicts, as underlined by Haeberli et al. (2016). For example, multipurpose projects for hazard mitigation by flood retention, hydropower, and water reservoir can be implemented generating potential synergies. In contrast, projects that imply the construction of infrastructures may be in strong conflict with the presence of protected natural areas and landscape. Synergies and/or conflicts can also emerge when lakes present hazardous conditions: they can reduce the attractiveness of the territories where the lakes are located because of the connected risk; on the other hand, they may also enhance the visibility and thus the frequentation (e.g. Lago Effimero on the east face of the Monte Rosa Massif; Mortara and Mercalli 2002). The comprehensive matrix-type approach proposed by Haeberli et al. (2016) can be applied to single cases for a first evaluation of these aspects. Moreover, surveys with tourists and local populations on their perception of the different values of glacier lakes could be proposed and performed. Finally, proper communication to decision makers and stakeholders (i.e. usable science; Giordan et al. 2015) has to be favored in order to promote integrative/participative planning and management of lakes at all levels.

5 CONCLUSION

The application of the proposed methodology aims at identifying (by updating the glacier lake inventory) and selecting (by applying the approach for lake socio-environmental value assessment) lakes to be prioritized for sustainable management strategies. Hundreds (337) of glacier lakes were identified in the Aosta Valley region, covering a total surface of about 1.55 km^2 (0.05% of the entire region). In 2015, glaciers lost 3% of their surface with respect to the 2006-2007 inventory, while the total number of lakes doubled and their area increased of approximately 30%. These newly formed glacier lakes have undergone a semi-quantitative assessment of their socio-environmental value in order to obtain a ranking list. Those performing the highest scores were then evaluated based on information acquired directly by field surveys and indirectly by existing literature. Results showed the robustness of the assessment considering some of the highest scored lakes (e.g. Lago del Miage, lakes at Rutor Glacier, etc.) and mountain sectors (Mont Blanc and Matterhorn areas).

The proposed assessment facilitates the determination of the most promising lakes and related territories for potential sustainable development by dedicated projects (e.g. educational, tourism, geoconservation, etc.) taking into account possible emerging synergies and conflicts. Information about the interaction of the lakes and surrounding areas with natural instabilities provides a rationale for excluding sites in relation to potential risk conditions and, in turn, selecting those that provide benefits without risks.

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References

Aggarwal A, Jain SK, Lohani AK, Jain N (2016) Glacial lake outburst flood risk assessment using combined approaches of remote sensing, GIS and dam break modelling. Geomat Nat Haz Risk 7(1):18-36. https://doi.org/10.1080/19475705.2013.862573

Allen SK, Schneider D, Owens IF (2009) First approaches towards modelling glacial hazards in the Mount Cook region of New Zealand’s Southern Alps. Nat Hazards Earth Syst Sci 9:481-499. https://doi.org/10.5194/nhess-9-481-2009

Allen SK, Zhang G, Wang W, Yao T, Bolch T (2019) Potentially dangerous glacial lakes across the Tibetan Plateau revealed using a large-scale automated assessment approach. Sci Bull 64(7):435-445. https://doi.org/10.1016/j.scib.2019.03.011

Ballantyne CK (2002) Paraglacial geomorphology. Quat Sci Rev 21(18-19):1935-2017. https://doi.org/10.1016/S0277-3791(02)00005-7

Bertotto S, Perotti L, Bacenetti M, Damiano E, Marta C, Giardino M (2015) Integrated Geomatic Techniques for Assessing Morphodynamic Processes and Related Hazards in Glacial and Periglacial Areas (Western Italian Alps) in a Context of Climate Change. In: Lollino G, Manconi A, Clague J, Shan W, Chiarle M (ed) Engineering Geology for Society and Territory 1:173-176. Springer, Cham. https://doi.org/10.1007/978-3-319-09300-0_33

Bolch T, Peters J, Yegorov A, Pradhan B, Buchroithner M, Blagoveschchensky V (2011) Identification of potentially dangerous glacial lakes in the northern Tien Shan. Nat Hazards 59(3):1691-1714. https://doi.org/10.1007/s11069-011-9860-2

Bollati I, Smiraglia, Pelfini M (2013) Assessment and Selection of Geomorphosites and Trails in the Miage Glacier Area (Western Italian Alps). Environ Manage 51:951-967. https://doi.org/10.1007/s00267-012-9995-2

Bollati I, Leonelli G, Vezzola L, Pelfini M (2015) The role of Ecological Value in Geomorphosite assessment for the Debris-Covered Miage Glacier (Western Italian Alps) based on a review of 2.5 centuries of scientific study. Geoheritage 7(2):119-135. DOI 10.1007/s12371-014-0111-2

Bollati I, Crosa Lenz B, Zanoletti E, Pelfini M (2017) Geomorphological mapping for the valorization of the alpine environment. A methodological proposal tested in the Loana Valley (Sesia Val Grande Geopark, Western Italian Alps). J Mt Sci 14(6):1023-1038. DOI: 10.1007/s11629-017-4427-7

Brunner MI, Gurung AB, Zappa M, Zekollari H, Farinotti D, Stähli M (2019) Present and future water scarcity in Switzerland: Potential for alleviation through reservoirs and lakes. Sci Total Environ 666:1033-1047. https://doi.org/10.1016/j.scitotenv.2019.02.169

Buckel J, Otto JC, Prasicek G, Keuschnig M (2018) Glacial lakes in Austria – distribution and formation since the Little Ice Age. Glob Planet Chang 164:39-51. https://doi.org/10.1016/j.gloplacha.2018.03.003

Carrivick JL (2010) Dam break - Outburst flood propagation and transient hydraulics: a geosciences perspective. J Hydrol 380(3-4):338-355. https://doi.org/10.1016/j.jhydrol.2009.11.009

Carrivick JL, Tweed FS (2013) Proglacial lakes: character, behavior and geological importance. Quat Sci Rev 78:34-52. https://doi.org/10.1016/j.quascirev.2013.07.028

Čiamporová-Zaťovičová Z, Čiampor F (2017) Alpine lakes and ponds - a promising source of high genetic diversity in metapopulations of aquatic insects. Inland Waters 7(1):109–117. https://doi.org/10.1080/20442041.2017.1294361

Citterio M, Diolaiuti GA, Smiraglia C, D'Agata C, Carnielli T, Stella G, Siletto GB (2007) The fluctuations of Italian glaciers during the last century: a contribution to knowledge about alpine glacier changes. Geogr Ann A 89(3):164-1821. https://doi.org/10.1111/j.1468-0459.2007.00316.x

Colombo N, Bocchiola D, Martin M, Confortola G, Salerno F, Godone D, D'Amico ME, Freppaz M (2019a) High export of nitrogen and dissolved organic carbon from an Alpine glacier (Indren Glacier, NW Italian Alps). Aquat Sci 81:74. doi.org/10.1007/s00027-019-0670-z

Colombo N, Salerno F, Martin M, Malandrino M, Giardino M, Serra E, Godone D, Said-Pullicino D, Fratianni S, Paro L, Tartari G, Freppaz M (2019b) Influence of permafrost, rock and ice glaciers on chemistry of high-elevation ponds (NW Italian Alps). Sci Total Environ 685:886–901. https://doi.org/10.1016/j.scitotenv.2019.06.233

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(5):336. https://doi.org/10.3390/w9050336

Cook SJ, Kougkoulos I, Edwards LA, Dortch J, Hoffmann D (2016) Glacier change and glacial lake outburst flood risk in the Bolivian Andes. Cryosphere 10:2399-2413. https://doi.org/10.5194/tc-10-2399-2016

D'Amico ME, Pintaldi E, Sapino E, Colombo N, Quaglino E, Stanchi S, Navillod E, Rocco R, Freppaz M (2020) Soil types of Aosta Valley (NW-Italy). J Maps 16(2):755-765. DOI: 10.1080/17445647.2020.1821803

Deline P, Chiarle M, Mortara G (2002) The frontal ice avalanche of Frebouge glacier (Mont Blanc Massif, Valley of Aosta, NW Italy) on 18 September 2002. Geogr Fis Dinam Quat 25: 101-104. http://www.glaciologia.it/wp-content/uploads/FullText/full_text_25_2/02_GFDQ_25_2_Deline_101_104.pdf

Deline P, Chiarle M, Mortara G (2004) The July 2003 Frébouge debris flows (Mont Blanc Massif, Valley of Aosta, Italy): water pocket outburst flood and ice avalanche damming. Geogr Fis Dinam Quat 27:107-111. http://www.glaciologia.it/wp-content/uploads/FullText/full_text_27_2/01_GFDQ_27_2_Deline_107_111.pdf

Diolaiuti GA, Citterio M, Carnielli T, D'agata C, Kirkbride M, Smiraglia C (2006) Rates, processes and morphology of fresh-water calving at Miage Glacier (Italian Alps). Hydrol Process 20:2233–2244. https://doi.org/10.1002/hyp.6198

Diolaiuti G, Smiraglia C (2010) Changing glaciers in a changing climate: how vanishing geomorphosites have been driving deep changes in mountain landscapes and environments. Géomorphologie 16(2):131-152. https://doi.org/10.4000/geomorphologie.7882.

Diolaiuti G, Kirkbride MP, Smiraglia C, Benn DI, D'Agata C, Nicholson L (2017) Calving processes and lake evolution at Miage glacier, Mont Blanc, Italian Alps. Ann Glaciol 40:207-214. https://doi.org/10.3189/172756405781813690

Drenkhan F, Guardamino L, Huggel C, Frey H (2018) Current and future glacier and lake assessment in the deglaciating Vilcanota-Urubamba basin, Peruvian Andes. Glob Planet Chang 169:105-118. https://doi.org/10.1016/j.gloplacha.2018.07.005.

Drenkhan F, Huggel C, Guardamino L, Haeberli W (2019) Managing risks and future options from new lakes in the deglaciating Andes of Peru: the example of the Vilcanota-Urubamba basin. Sci Total Environ 665:465-483. https://doi.org/10.1016/j.scitotenv.2019.02.070

Dutto F, Mortara G (1992) Rischi connessi con la dinamica glaciale nelle Alpi Italiane. Geogr Fis Din Quat 15:85-99. http://www.glaciologia.it/wp-content/uploads/FullText/full_text_15_1_2/11_GFDQ_15_1_2_Dutto_85_99.pdf

Emmer A, Vilímek V, Klimeš J, Cochachin A (2014) Glacier retreat, lakes development and associated natural hazards in Cordilera Blanca, Peru. In: Shan W, Guo Y, Wang F, Marui H, Strom A (ed) Landslides in Cold Regions in the Context of Climate Change. Environ Sci Eng. Springer, Cham, pp 231-252. https://doi.org/10.1007/978-3-319-00867-7_17

Emmer A, Merkl S, Mergili M (2015) Spatiotemporal patterns of high-mountain lakes and related hazards in western Austria. Geomorphology 246:602–616. https://doi.org/10.1016/j.geomorph.2015.06.032

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. https://doi.org/10.1016/j.catena.2016.07.032

Emmer A, Harrison S, Mergili M, Allen S, Frey H, Huggel C (2020) 70 years of lake evolution and glacial lake outburst floods in the Cordillera Blanca (Peru) and implications for the future. Geomorphology 365:107178. https://doi.org/10.1016/j.geomorph.2020.107178

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

GAPHAZ (2017) Assessment of Glacier and Permafrost Hazards in Mountain Regions. Technical Guidance Document. Standing Group on Glacier and Permafrost Hazards in Mountains (GAPHAZ) of the International Association of Cryospheric Sciences (IACS) and the International Permafrost Association (IPA). Zurich, Switzerland/Lima, Peru.

Gardelle J, Arnaud Y, Berthier E (2011) Contrasted evolution of glacial lakes along the Hindu Kush Himalaya mountain range between 1990 and 2009. Glob Planet Chang 75(1–2):47-55. https://doi.org/10.1016/j.gloplacha.2010.10.003

Giordan D, Manconi A, Allasia P, Bertolo D (2015) Brief Communication: On the rapid and efficient monitoring results dissemination in landslide emergency scenarios: the Mont de La Saxe case study. Nat Hazards Earth Syst Sci 15(9):2009-2017. https://doi.org/10.5194/nhess-15-2009-2015

Girres JF, Touya G (2010) Quality Assessment of the French OpenStreetMap DatasetTransactions in GIS 14(4):435-459. https://doi.org/10.1111/j.1467-9671.2010.01203.x

Goldrick G, Bishop P (2007) Regional analysis of bedrock stream long profiles: evaluation of Hack's SL form, and formulation and assessment of an alternative (the DS form). Earth Surf Process Landf 32(5):649-671. https://doi.org/10.1002/esp.1413

Gould WR, Patla DA, Daley R, Corn PS, Hossack BR, Bennetts R, Peterson CR (2012) Estimating occupancy in large landscapes: evaluation of amphibian monitoring in the Greater Yellowstone Ecosystem. Wetlands 32(2):379-389. https://doi.org/10.1007/s13157-012-0273-0

Gray M (2013) Geodiversity: Valuing and conserving abiotic nature, second edition. Wiley Blackwell. 508 pp.

Haeberli W, Bütler M, Huggel C, Müller H, Schleiss A (2013) Neue Seen als Folge des Gletscherschwundes im Hochgebirge - Chancen und Risiken. Formation de nouveaux lacs suite au recul des glaciers en haute montagne - chances et risques. Zürich, Hochschulverlag AG.

Haeberli W, Bütler M, Huggel C, Lehmann Friedli T, Schaub Y, Schleiss AJ (2016) New lakes in deglaciating high-mountain regions - opportunities and risks. Clim Chang 139(2):202-214. https://doi.org/10.1007/s10584-016-1771-5

Haeberli W, Schaub Y, Huggel C (2017) Increasing risks related to landslides from degrading permafrost into new lakes in de-glaciating mountain ranges. Geomorphology 293:405-417. https://doi.org/10.1016/j.geomorph.2016.02.009

Hock R, Rasul G, Adler C, Cáceres B, Gruber S, Hirabayashi Y, Jackson M, Kääb A, Kang S, Kutuzov S, Milner Al, Molau U, Morin S, Orlove B, Steltzer H (2019) High Mountain Areas. In: Pörtner HO, Roberts DC, Masson-Delmotte V, Zhai P, Tignor M, Poloczanska E, Mintenbeck K, Alegría A, Nicolai M, Okem A, Petzold J, Rama B, Weyer NM (ed) IPCC Special Report on the Ocean and Cryosphere in a Changing Climate.

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. Can Geotech J 39(2):316-330. https://doi.org/10.1139/t01-099

Huggel C, Kääb A, Haeberli W, Krummenacher B (2003). Regional-scale GIS-models for assessment of hazards from glacier lake outbursts: evaluation and application in the Swiss Alps. Nat Hazards Earth Syst Sci 3(6):647-662. https://doi.org/10.5194/nhess-3-647-2003

Huggel C, Haeberli W, Kääb A, Bieri D, Richardson S (2004) An assessment procedure for glacial hazards in the Swiss Alps. Can Geotech J 41(6):1068-1083. https://doi.org/10.1139/t04-053

Huggel C, Carey M, Emmer A, Frey H, Walker-Crawford N, Wallimann-Helmer I (2020) Anthropogenic climate change and glacier lake outburst flood risk: local and global drivers and responsibilities for the case of lake Palcacocha, Peru. Nat Hazards Earth Syst Sci 20(8) :2175-2193. https://doi.org/10.5194/nhess-20-2175-2020

Jenks GF (1967) The data model concept in statistical mapping. International Yearbook of Cartography 7:186-190.

Kapitsa V, Shahgedanova M, Machguth H, 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. Nat Hazards Earth Syst Sci 17(10):1837-1856. https://doi.org/10.5194/nhess-17-1837-2017

Kellner E, Brunner MI (2021) Reservoir Governance in World's Water Towers Needs to Anticipate Multi-purpose Use. Earth’s Future 9(1): e2020EF001643. https://doi.org/10.1029/2020EF001643

Laute K, Beylich AA (2021) Recent glacier changes and formation of new proglacial lakes at the Jostedalsbreen ice cap in southwest Norway. In Landscapes and Landforms of Norway (pp. 71-95). Springer, Cham.

Linsbauer A, Paul F, Hoelzle M, Frey H, Haeberli W (2009) The Swiss Alps without glaciers - a GIS-basedmodelling approach for reconstruction of glacier beds. In: Purves R, Gruber S, Straumann R, Hengl T (ed) Proceedings of Geomorphometry, pp 243-247. http://geomorphometry.org/system/files/linsbauer2009geomorphometry.pdf

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. J Geophys Res 117:F03007. https://doi.org/10.1029/2011JF002313

Linsbauer A, Frey H, Haeberli W, Machguth H, Azam MF, Allen S (2016) Modelling glacier-bed overdeepenings and possible future lakes for glaciers in the Himalaya-Karakoram region. Ann Glaciol 57(71):119-130. https://doi.org/10.3189/2016AoG71A627

Lucchesi S, Giardino M, Perotti L (2013) Applications of high-resolution images and DTMs for detailed geomorphological analysis of mountain and plain areas of NW Italy. Eur J Remote Sens 46(1):216-233. https://doi.org/10.5721/EuJRS20134612

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). J Maps 10(3):409-423. https://doi.org/10.1080/17445647.2014.880226

Lucchesi S, Bertotto S, Chiarle M, Fioraso G, Giardino M, Nigrelli G (2019) Little Ice Age glacial systems and related natural instability processes in the Orco Valley (North-Western Italy). J Maps 15(2):142-152. https://doi.org/10.1080/17445647.2018.1564382

Magnin F, Haeberli W, Linsbauer A, Deline P, Ravanel L (2020) Estimating glacier-bed overdeepenings as possible sites of future lakes in the de-glaciating Mont Blanc massif (Western European Alps). Geomorphology 350:106913. https://doi.org/10.1016/j.geomorph.2019.106913

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

Marcello C, Meda P (2013) The rehabilitation design of the Beauregard Dam. In: 9th ICOLD European Club Symposium, Venice, Italy. https://www.semanticscholar.org/paper/The-rehabilitation-design-of-the-Beauregard-Dam-Marcello-Meda/9b0d7f1029fbf98a24abc18e111cb642a8bf81cd?p2df

Mergili M, Schneider JF (2011) Regional-scale analysis of lake outburst hazards in the southwestern Pamir, Tajikistan, based on remote sensing and GIS. Nat Hazards Earth Syst Sci 11(5):1447-146. https://doi.org/10.5194/nhess-11-1447-2011

Mergili M, Müller JP, Schneider JF (2013) Spatio-temporal development of high-mountain lakes in the headwaters of the Amu Darya River (Central Asia). Glob Planet Chang 107:13-24. https://doi.org/10.1016/j.gloplacha.2013.04.001

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. Prog Phys Geog 40(5):629-660. https://doi.org/10.1177%2F0309133316643926

Mölg N, Huggel C, Herold T, Storck F, Allen S, Haeberli W, Schaub Y, Odermatt D (2021) Inventory and evolution of glacial lakes since the Little Ice Age: Lessons from the case of Switzerland. Earth Surface Processes and Landforms 1-14. https://doi.org/10.1002/esp.5193

Mortara G, Mercalli L (2002) Il lago epiglaciale 'Effimero' sul ghiacciaio del Belvedere, Macugnaga, Monte Rosa. Nimbus 23-24:10-17.

Murphy MA, Dezzani R, Pilliod DS, Storfer A (2010). Landscape genetics of high mountain frog metapopulations. Mol Ecol 19(17):3634-3649. DOI: 10.1111/j.1365-294X.2010.04723.x

Nussbaumer S, Schaub Y, Huggel C, Walz A (2014) Risk estimation for future glacier lake outburst floods based on local land-use changes. Nat Hazards Earth Syst Sci 14(6):1611-1624. https://doi.org/10.5194/nhess-14-1611-2014

O'Callaghan JF, Mark DM (1984) The extraction of drainage networks from digital elevation data. Comput Gr Image Process 28(3):323-344. https://doi.org/10.1016/S0734-189X(84)80011-0

Orombelli G (2005) Il Ghiacciaio del Rutor (Valle d'Aosta) nella Piccola Età Glaciale. Geogr Fis Din Quat Suppl VII:239-251. http://www.glaciologia.it/wp-content/uploads/FullText/full_text_27_2/02_GFDQ_27_2_Deline_113_119.pdf

Ollier C (1981) Tectonics and Landforms. Longman, London. 324 pp.

Paul F, Kääb A, Haeberli W (2007) Recent glaciers changes in the Alps observed by satellite: consequences for future monitoring strategies. Glob Planet Chang 56(1-2):111-122. https://doi.org/10.1016/j.gloplacha.2006.07.007

Pelfini M, Bollati I (2014) Landforms and geomorphosites ongoing changes: Concepts and implications for geoheritage promotion. Quaest Geogr 33(1):131-143. https://doi.org/10.2478/quageo-2014-0009

Porter SC, Orombelli G (1980) Catastrophic rockfall of September 12, 1717 on the Italian flank of the Mont Blanc Massif. Zeit Geomorph Stuttgart 24(2):200-218.

Purdie H (2013) Glacier retreat and tourism: insights from New Zealand.Mt. Res Dev 33(4):463-472. https://doi.org/10.1659/MRD-JOURNAL-D-12-00073.1

Salerno F, Thakuri S, D'Agata C, Smiraglia C, Manfredi EC, Viviano G, Tartari G (2012) Glacial lake distribution in the Mount Everest region: uncertainty of measurement and conditions of formation. Glob Planet Chang 92-93:30-39. https://doi.org/10.1016/j.gloplacha.2012.04.001

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. Glob Planet Chang 120:81-91. https://doi.org/10.1016/j.gloplacha.2014.06.003

Salerno F, Thakuri S, Guyennon N, Viviano G, Tartari G (2016) Glacier melting and precipitation trends detected by surface area changes in Himalayan ponds. Cryosphere 10:1433-1448. https://doi.org/10.5194/tc-10-1433-2016

Salvatore MC, Zanoner T, Baroni C, Carton A, Banchieri FA, Viani C, Giardino M, Perotti L (2015) The state of Italian glaciers: a snapshot of the 2006–2007 hydrological period. Geogr Fis Din Quat 38(2):175-198. https://doi.org/10.4461/GFDQ.2015.38.16

Schaub Y, Haeberli W, Huggel C, Künzler M, Bründl M (2013) Landslides and new lakes in deglaciating areas: a risk management framework. In: Margottini C, Canuti P, Sassa K (eds) Landslide Science and Practice pp. 31-38. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-31313-4_5

Silva PG, Goy JL, Zazo C, Bardajm T (2003) Fault generated mountain fronts in Southeast Spain: geomorphologic assessment of tectonic and earthquake activity, Geomorphology 250:203-225. https://doi.org/10.1016/S0169-555X(02)00215-5

Smiraglia C, Azzoni RS, D'Agata C, Maragno D, Fugazza D, Diolaiuti GA (2015) The evolution of the Italian glaciers from the previous data base to the New Italian Inventory. Preliminary considerations and results. Geogr Fis Din Quat 38(1):79-87. https://doi.org/10.4461/GFDQ.2015.38.08

Stokes CR, Popovnin V, Aleynikov A, Gurney SD, Shahgedanova M (2007) Recent glacier retreat in the CaucasusMountains, Russia, and associated increase in supraglacial debris cover and supra-/proglacial lake development. Ann Glaciol 46:195-203. https://doi.org/10.3189/172756407782871468

Terrier S, Jordan F, Schleiss AJ, Haeberli W, Hugge LC, Künzler M (2011) Optimized and adapted hydropower management considering glacier shrinkage scenarios in the Swiss Alps. In: Schleiss A, Boes RM (ed) Proceedings of the International Symposium on Dams and Reservoirs Under Changing Challenges. Taylor & Francis Group, pp 497-508. http://infoscience.epfl.ch/record/167089/files/2011-774_Terrier_Jordan_Schleiss_Haeberli_Huggel_Kunzler_Optimized_and_adapted_hydropower_management_considering_glacier_shrinkage_scenarios_in_the_swiss_alps.pdf

Tiberti R (2018) Can satellite ponds buffer the impact of introduced fish on newts in a mountain pond network? Aquat Conserv: Mar Freshw Ecosyst (2):457-465. https://doi.org/10.1002/aqc.2858

Tiberti R, Buscaglia F, Callieri C, Rogora M, Tartari G, Sommaruga R (2020) Food web complexity of high mountain lakes is largely affected by glacial retreat. Ecosystems 23:1093-1106. https://doi.org/10.1007/s10021-019-00457-8

Tognetto F, Perotti L, Viani C, Colombo N, Giardino M (2021) Geomorphology and geosystem services of the Indren-Cimalegna area (Monte Rosa massif – Western Italian Alps). J Maps 17(2):161-172. https://doi.org/10.1080/17445647.2021.1898484

Viani C, Giardino M, Huggel C, Perotti L, Mortara G (2016) An overview of glacier lakes in the Western Italian Alps from1927 to 2014 based on multiple data sources (historical maps, orthophotos and reports of the glaciological surveys). Geogr Fis Din Quat 39(2):203-214. https://doi.org/10.4461/GFDQ.2016.39.19

Viani C (2018) Inventories of glacier lakes in the Western Italian Alps from the 1930s to 2012. PANGEA https://doi.org/10.1594/PANGAEA.896023

Viani C, Machguth H, Huggel C, Godio A, Franco D, Perotti L, Giardino M (2020) Potential future lakes from continued glacier shrinkage in the Aosta Valley Region (Western Alps, Italy). Geomorphology 355:107068. https://doi.org/10.1016/j.geomorph.2020.107068

Vione D, Colombo N, Said-Pullicino D, Bocchiola D, Confortola G, Salerno F, Viviano G, Fratianni S, Martin M, Godone D, Freppaz M (2021) Seasonal variations in the optical characteristics of dissolved organic matter in glacial pond water. Sci Total Environ 759:143464. https://doi.org/10.1016/j.scitotenv.2020.143464

Wang SJ, Zhou LY (2019) Integrated impacts of climate change on glacier tourism. Adv Clim Change Res 10(2):71-79. https://doi.org/10.1016/j.accre.2019.06.006

Westoby MJ, Glasser NF, Brasington J, Hambrey MJ, Quincey DJ, Reynolds JM (2014) Modelling outburst floods from moraine-dammed glacial lakes. Earth-sci Rev 134:137-159. https://doi.org/10.1016/j.earscirev.2014.03.009

Westoby MJ, Brasington J, Glasser NF, Hambrey MJ, Reynolds JM, Hassan MAAM, Lowe A (2015) Numerical modelling of glacial lake outburst floods using physically based dam-breach models. Earth Surf Dynam 3:171-199 https://doi.org/10.5194/esurf-3-171-2015

Wichmann V (2017) The Gravitational Process Path (GPP) model (v1.0) – a GIS-based simulation framework for gravitational processes. Geosci Model Dev 10:3309–3327. https://doi.org/10.5194/gmd-10-3309-2017

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. Sci Total Environ 468-469:S71-84. https://doi.org/10.1016/j.scitotenv.2012.11.043

Zekollari H, Huss M, Farinotti D (2019) Modelling the future evolution of glaciers in the European Alps under the EURO-CORDEX RCM ensemble. Cryosphere 13:1125-1146. https://doi.org/10.5194/tc-13-1125-2019

Zemp M, Haeberli W, Hoelzle M, Paul F (2006) Alpine glaciers to disappear within decades? Geophys Res Lett 33(13):L13504. https://doi.org/10.1029/2006GL026319

Zhang G, Yao T, Piao S, Bolch T, Xie H, Chen D, Gao Y, O'Reilly CM, Shum CK, Yang K, Yi S, Lei Y, Wang W, He Y, Shang K, Yang X, Zhang H (2017) Extensive and drastically different alpine lake changes on Asia's high plateaus during the past four decades. Geophys Res Lett 44(1):252-260. https://doi.org/10.1002/2016GL072033

Zwoliński Z (2008) Designing a map of the geodiversity of landforms in Poland. IAG and AIGEO International Meeting, Environmental Analysis and Geomorphological Mapping for a Sustainable Development, Addis Ababa, Ethiopia. Abstract Book, 18-22.

Zwoliński Z (2009) The routine of landform geodiversity map design for the Polish Carpathian Mts. Landform Analysis 11:77-85.

Editor	
The two reviewers have now commented on your revised paper. After consideration, the editor Professor Helmut Haberl and I invite you to undertake a minor revision of your manuscript.	We thank the editors for the thorough assessment of the manuscript. We replied to each individual area of concern expressed by the reviewers as it can be read below.
Comment	**Response**
Reviewer #1	
I thank the authors for their careful consideration and thorough incorporation of my suggestions. Readability and comprehensibility of the manuscript greatly improved compared to its previous version. I welcome the addition of several new text passages (particularly in L57-66, L116-124, L208-247, L336-353, L394-410, and L521-634), which provide necessary additional information, greatly improve this study's comprehensibility and overall strengthen the lake value assessment approach. In my opinion, especially the new section 4.4, "Advantages, limits, and possible implementations of the applied methodology" (L521-634), helps with setting this study's methodological approach in a greater scientific context. I respect the author's choice of using the GPP model for GLOF-runout modelling, which is now adequately introduced (L336-353) and discussed (L597-606). I also concur with the author's decision to omit the LGLOB value in their methodological approach, which again helped with the study's comprehensibility and structure. I agree with Reviewer #2's proposal of including a methodological flowchart and found the new Figure 2 to be very helpful in understanding the proposed methodology to quantify a lake's socio-environmental value. Likewise, following the editor's suggestion, I prefer the shortened manuscript title.	We thank the reviewer for the valuable comments that helped us to improve the previous manuscript.
However, I still have some minor comments, most of which regard the newly added GLOF explanatory paragraph (L57-66):	All comments have been addressed, providing an item-by-item response to each comment as it can be read in our responses below.
L57-58 and L64-66: Consider merging these two sentences into one.	**L57-60** Amended
L6: In the list of GLOF conditioning factors, what is meant with "geometry"? I assume that you mean the geometry of the moraine dam - please alter the sentence structure to clarify this.	**L62** Amended
L62-64: This is correct but the formation of displacement waves is not the only process that can lead to dam overtopping/breaching. Other processes, for example, include the sudden inputs of large quantities of water by surface runoff into the lake during heavy precipitation events, piping, or the abrupt structural failure of the moraine dam caused by processes like wastage of a buried ice-core or seismic ground shaking. Please rephrase.	**L65-68** We agree with the reviewer about adding this additional information. We modified the sentence accordingly
An additional minor comment refers to the Figure 5's caption (L38): What is "sky	**L40** Agreed and amended.

tourism"? Based on this paper's context I guess that you mean "ski tourism".	
Reviewer #2	
Thank you for revising your manuscript in line with reviewer's comments and suggestions. Thank you also for presenting the concept of geosystem services - regulating, supporting, provisioning and cultural - in the introduction in more detail. This is analogical to well-established classification of ecosystem services and it makes sense to be used in this context in my opinion.	We thank the reviewer for the valuable comments that helped us to improve the previous manuscript.
What is, however, confusing is that you do not further work with this concept in your study (instead, you come up with another concept of 'glacial lake value' (called socio-environmental value in places (?)) comprised of 'geo-environmental value', 'interaction with human activities' and 'interaction with natural instabilities'). Linking these different concepts (explaining the difference and justifying the need for them both should be at least discussed in a separate discussion or methodological section) and a strict use of clear terminology would increase the conceptual understandability of the study substantially.	**L176-185** In order to better underline the link between geosystem services and the socio-environmental value mentioned in the present manuscript, we implemented the subsection "3.2 Assessment of the socio-environmental value of glacier lakes at the regional scale". **L176,537,656** Moreover, we simplified the terminology in order to increase the conceptual understandability of the study (e.g. we used the term "socio-environmental value" throughout the manuscript instead of "glacier lake value").
One of the main objectives of this study is to present an approach for the assessment of glacier lakes value / socio-environmental value of lakes. As mentioned before, I appreciate the amount of work done and I'm in favour of such assessments in general. However, some of the assessed characteristics (parameters) are defined in a way that re-use of this methodology is fairly limited. For instance, it is not clear what is an evidence of presence / absence of geomorphological features nor how it is assessed; in addition, it is not clear why is it supposed to (how does it) influence geo-environmental value?). Please provide illustrative examples (perhaps a supplement) for the reproducible assessments of individual parameters (i.e. an example of a lake with poor evidence of geomorphological influence; an example of a lake with good evidence of geomorphological influence, etc.).	**L262-272** We modified the paragraph related to the *Geomorphological features evidence* in order to better explain the assessment flow of the parameter. We also specified the importance of evaluating the mentioned parameter for the assessment of the lake geo-environmental value. **Figure 5** Considering the necessity of providing illustrative examples, we modified Fig. 5 by substituting the image in panel "a" in order to include lakes with both good and poor geomorphological features evidence (as underlined in the figure caption). If possible, we would avoid adding further material, since we already specified the assessment flow for the geomorphological feature evidence (**L262-272**), and we also provided good illustrative examples in Fig. 5. In addition, adding illustrative examples of e.g. single/multiple lakes, presence/absence of human settlements, socio-economic features would be rather ineffective given the straightforward meaning of these parameters.

Additional modification	**L534-652** We divided the subsection "4.4 Advantages, limits, and possible implementations of the applied methodology" in three related paragraphs: "4.4.1 Advantages", "4.4.2 Limits", "4.4.3 Possible implementations". We think that this solution could improve the organization and readability of the manuscript. **Figure 5f** We substituted the previous photograph in black and withe with the actual version in colors.

Figure

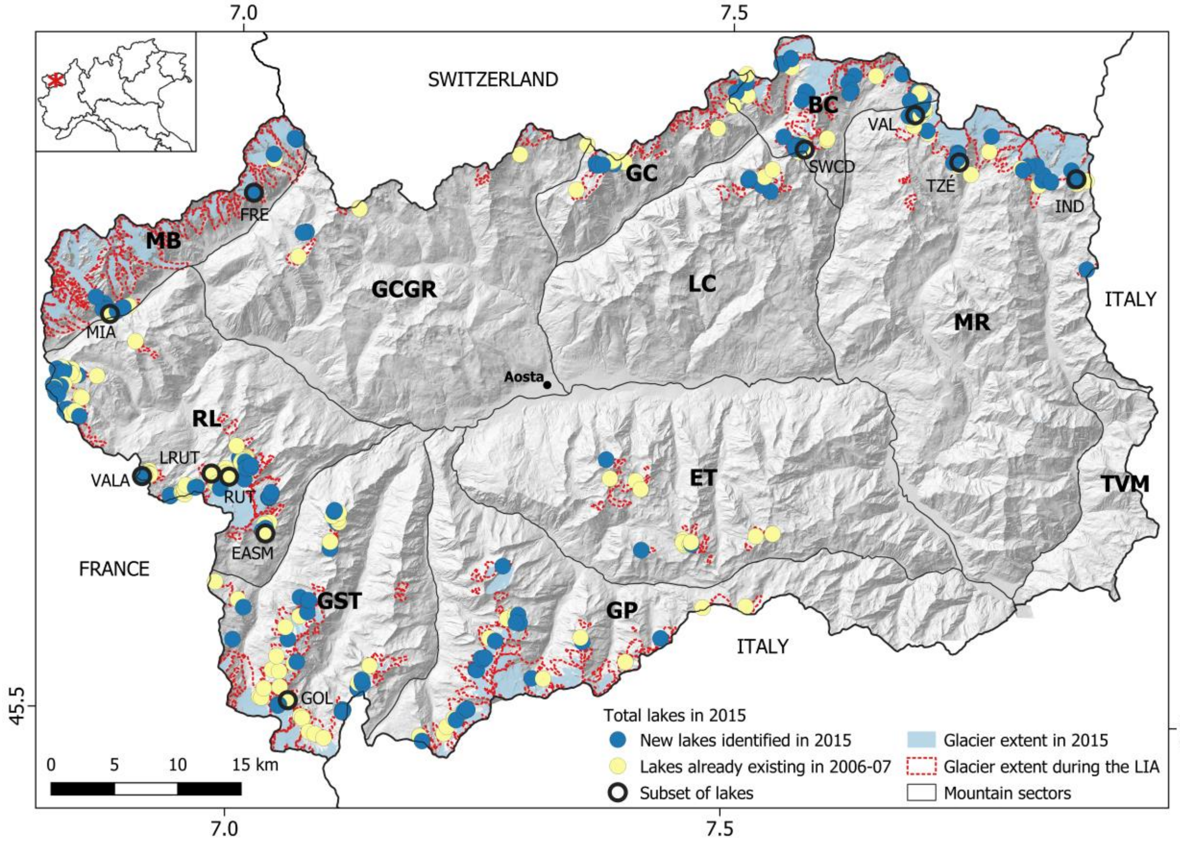


Figure 1. Map of the study area showing: the glacier extent during the LIA and in the year 2015; glacier lakes identified in 2015, separating new lakes firstly recognized in 2015 (blue dots) and lakes already existing in the previous inventory of 2006-2007 (yellow dots). Bold circles with associated abbreviations indicate a subset of specific lakes mentioned in the paper: Indren (IND), Tzére (TZÉ), Valtournenche (VAL), South West Château des Dames (SWCD), Frebouzie (FRE), Miage (MIA), Valaisan (VALA); Lago del Rutor (LRUT), Rutor (RUT), Eastern Morion (EASM), Goletta (GOL). Mountain sectors (abbreviations in bold in the map) are: Monte Rosa (MR), Bouquetins-Cervino (BC) also named Matterhorn, Luseney-Cian (LC), Gelé-Collon (GC), Grand Combin-Mont Velan + Grande Rochère-Grand Golliaz (GCGR), Dolent-Argentière-Trient + Monte Bianco + Trélatête (MB) also named Mont Blanc, Rutor-Lechuad (RL), Gran Sassière-Tsanteleina (GST), Gran Paradiso + Rosa dei Banchi (GP), Emilius-Tersiva (ET), and Tre Vescovi-Mars (TVM). The base map is the hillshade derived from 2008 LIDAR DTM of the Aosta Valley Region.

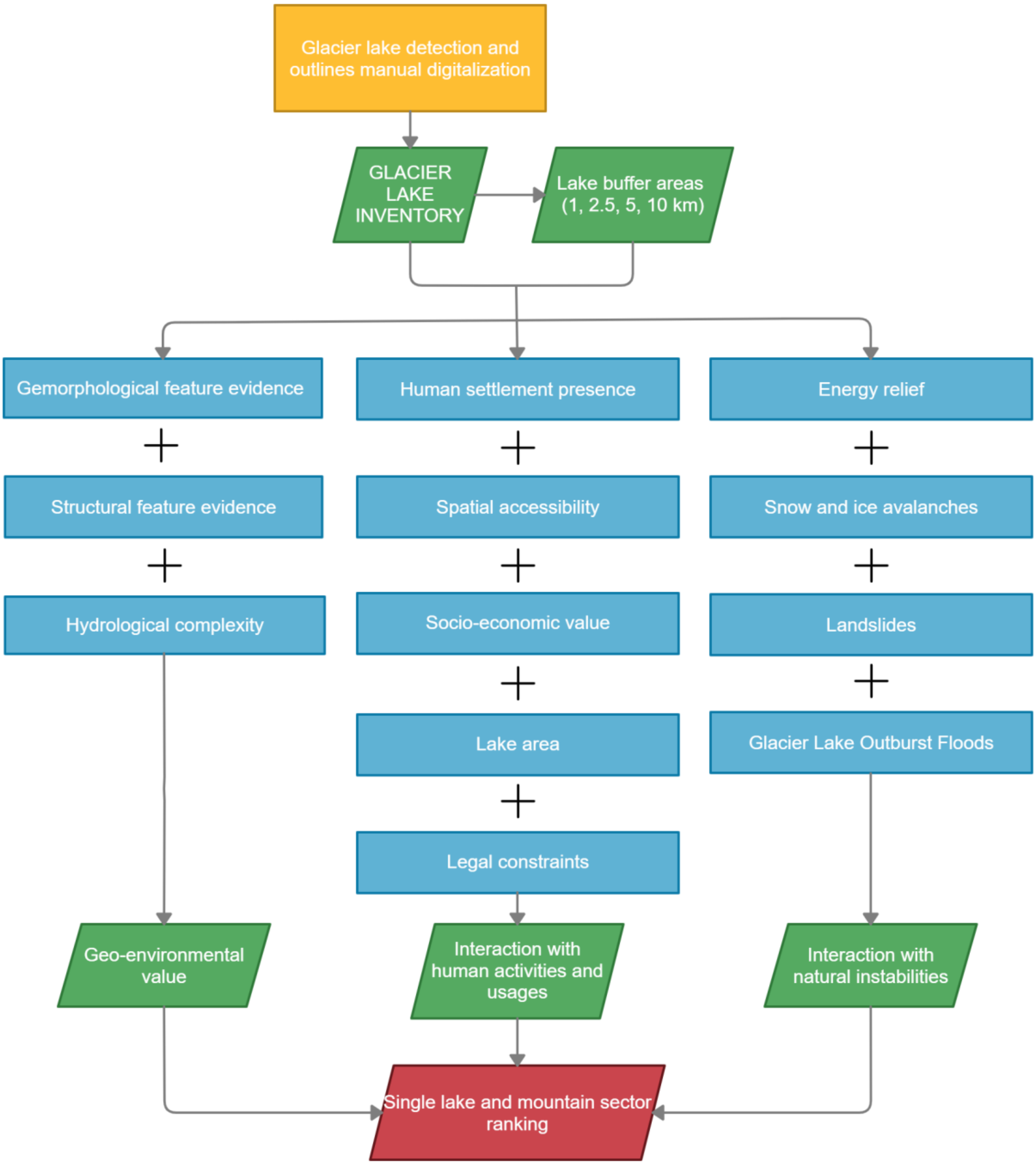
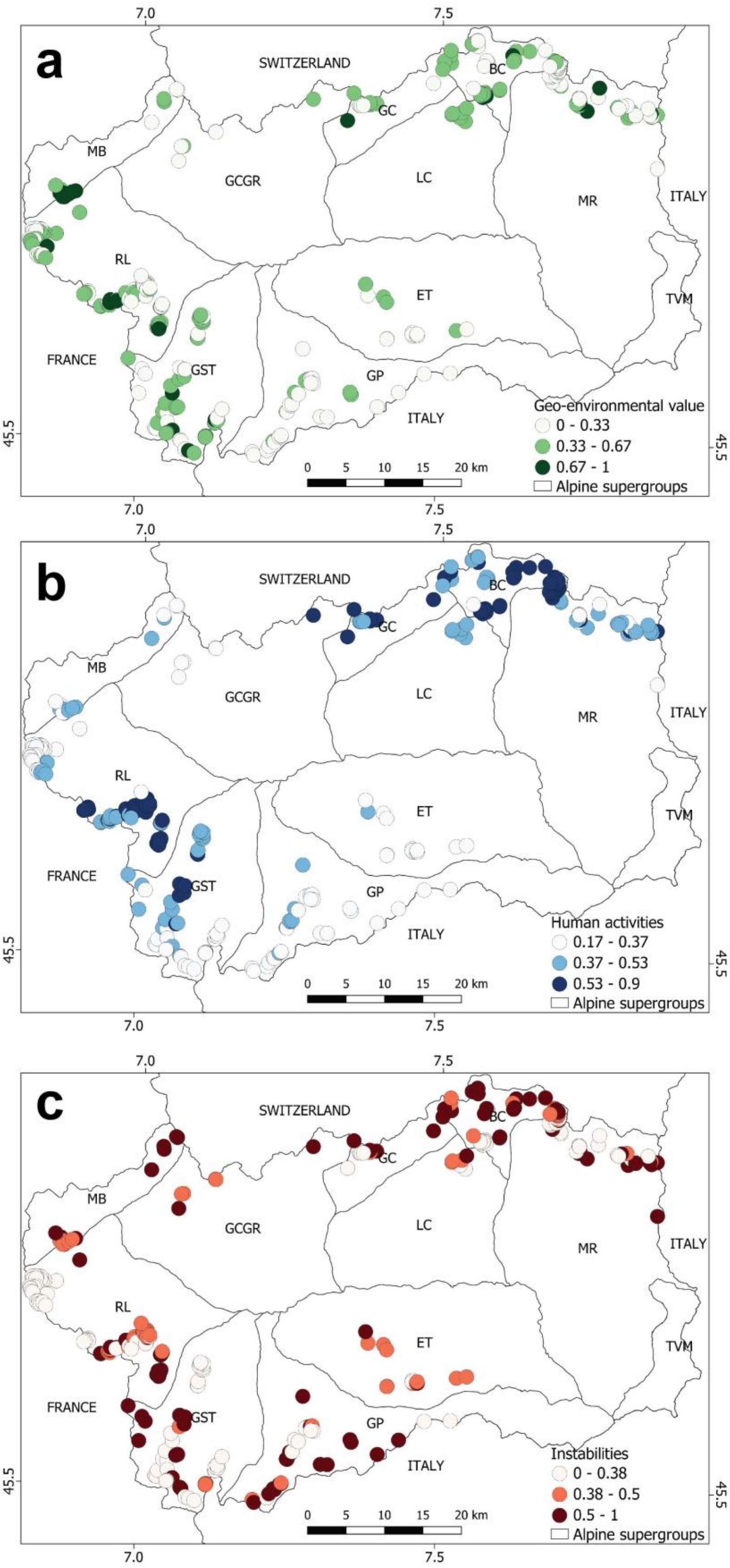


Figure 2. Flowchart of the overall methodological approach adopted in the present study.



a
SWITZERLAND
BC
GC
MB
GCGR
LC
MR
ITALY
RL
ET
TVM
FRANCE
GST
GP
ITALY
Geo-environmental value
0 - 0.33
0.33 - 0.67
0.67 - 1
Alpine supergroups
0 5 10 15 20 km
7.0
7.5
45.5
b
Human activities
0.17 - 0.37
0.37 - 0.53
0.53 - 0.9
Alpine supergroups
c
Instabilities
0 - 0.38
0.38 - 0.5
0.5 - 1
Alpine supergroups

Figure 3. Maps showing the results obtained by single lakes according to: a) geo-environmental value (LGEV), b) human activities (LHA) and, c) instabilities (LI). Abbreviations refer to mountain sectors reported in the caption of Fig. 1.

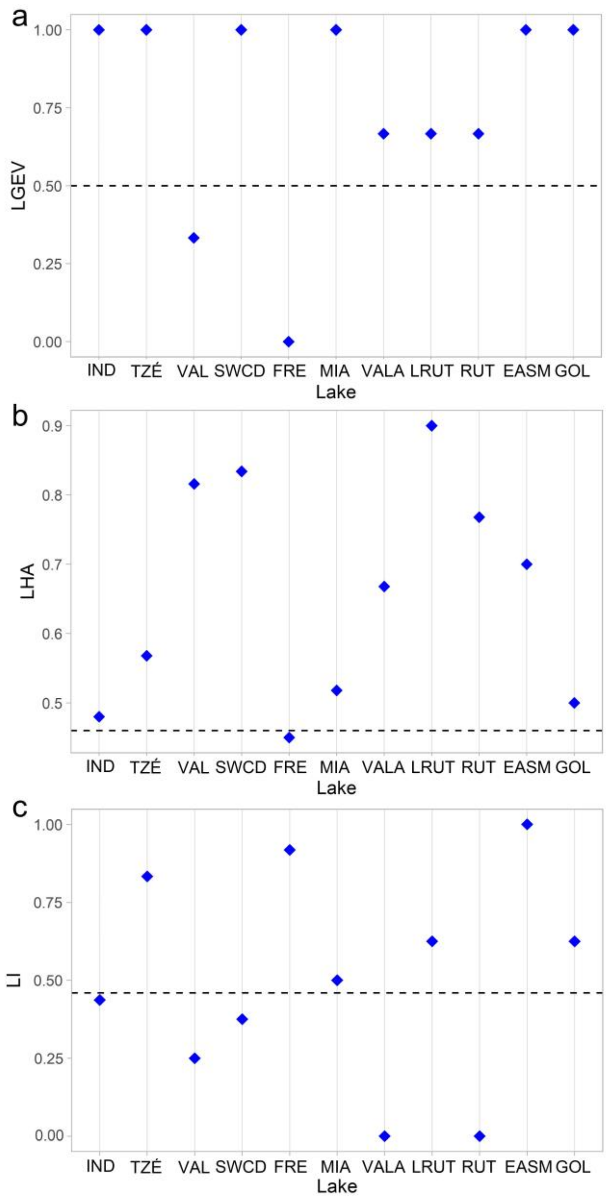


Figure 4. Indexed single lake value (ISLV) (blue rhombi) for a) geo-environmental value (LGEV), b) human activities (LHA), and c) instabilities (LI) for the subset of lakes that separately showed highest indexed value with respect to the average values of all 337 lakes. Average values of all 337 lakes are indicated as black dashed lines. Details of calculations are reported in Tab. 2. On the X axes the abbreviations of the lake names are reported: IND = Indren; TZÉ = Tzére; VAL = Valtournenche; SWCD = South West Château des Dames (Gran Lago); FRE = Frebouzie; MIA = Miage; VALA = Valaisan; LRUT = Rutor (Lago del Rutor); RUT = Rutor; EASM = Eastern Morion; GOL = Goletta. Please note that panels have different Y axes.

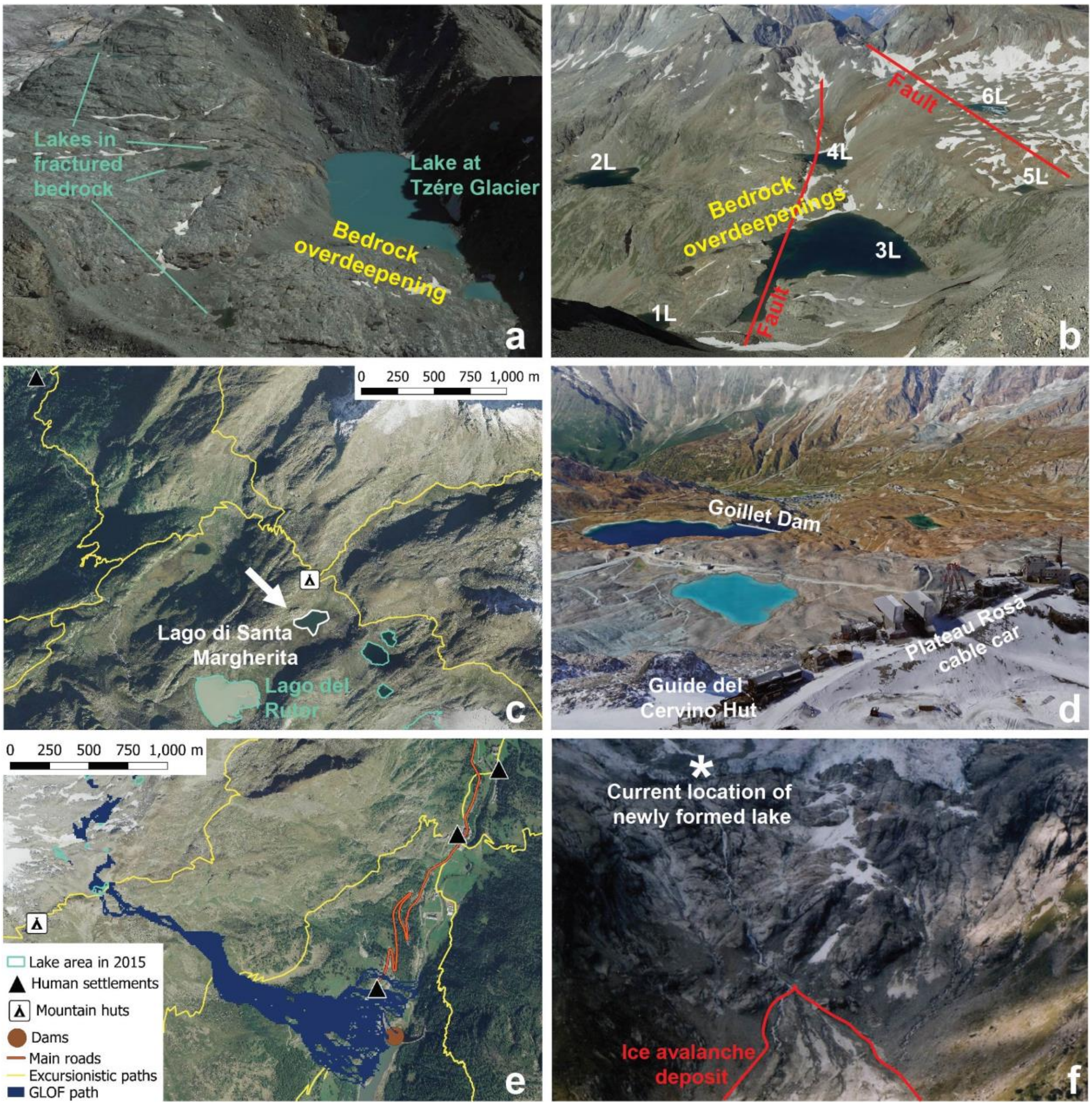


Figure 5. Examples of lakes performing the highest scores in the three categories of the assessment. Geo-environmental value: a) the lake at the Tzére Glacier (TZÉ lake, MR mountain sector). The figure shows also examples of lakes in fractured bedrock which received a low score due to absence of evident geomorphological features (3D image from Google Earth dated after 2016); b) lakes in the recently deglaciated areas of Balanselmo, Dragone, and South-West Château des Dames (SWCD, BC) glaciers (3D image from Google Earth dated after 2016). Interactions with human activities: c) Lago del Rutor (LRUT, RL) and Lago di Santa Margherita, the arrow indicates the location of the San Grato Chapel (basemap 2006 orthophoto, source Geoportale Nazionale); d) proglacial area of the Valtournenche Glacier with the presence of several lakes (VAL, BC) and evidence of human

exploitation for ski tourism (3D image from Google Earth dated after 2016). Interaction with natural instabilities: e) lakes at the Eastern Morion Glacier on the rock step facing on the Valgrisenche Valley (EASM, RL). Paved road and other human infrastructures in the valley floor are present (basemap 2006 orthophoto, source Geoportale Nazionale); f) deposit of the ice avalanche detached from the Frebouzie Glacier in 2002 (photo from Deline et al., 2002) and current location of the newly formed lake* (FRE, MB).

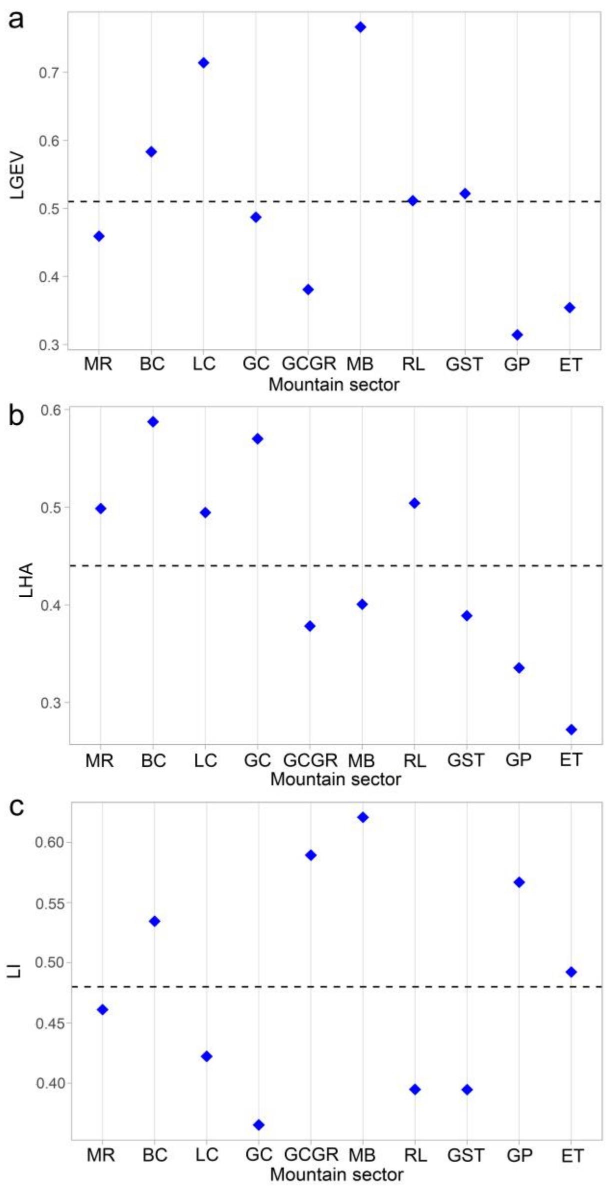


Figure 6. Indexed mountain sector value (IMSV) (blue rhombi) for a) geo-environmental value (LGEV), b) human activities (LHA), and c) instabilities (LI). Average values are indicated as black dashed lines. Details of calculations are reported in Tab. 2. On the X axes the abbreviations of the mountain sectors are reported: Monte Rosa (MR), Bouquetins-Cervino (BC) also named Matterhorn, Luseney-Cian (LC), Gele-Collon (GC), Grand Combin-Mont Velan + Grande Rochere-Grand Golliaz (GCGR), Dolent-Argentiere-Trient + Monte Bianco + Trelatete (MB) also named Mont Blanc, Rutor-Lechuad (RL), Gran Sassiere-Tsanteleina (GST), Gran Paradiso + Rosa dei Banchi (GP), and Emilius-Tersiva (ET). Please note that panels have different Y axes.

Table

GEO-ENVIRONMENTAL VALUE			
Parameter	*Value*	*Description*	*Data sources*
Geomorphological Features Evidence *	0 1	Absence of evident geomorphological features (e.g. basal till, fractured bedrock) Presence of evident geomorphological features (lateral/frontal moraine, bedrock overdeepening, or ice)	Lake inventory (dam type attribute); aerial orthophotos and/or high-resolution hillshade
Geological Features Evidence **	0 1	Absence of structural elements Presence of structural elements	Geological map (1:100,000) and structural elements buffered for 500 meters
Hydrological complexity *	0 0.5 1	One lake Two lakes More than two lakes (lake system)	Lake inventory LIA glacier extent
INTERACTION WITH HUMAN ACTIVITIES AND USAGES			
Human settlements presence **	0 0.33 0.67 1	>10km Any settlement within 10km Any settlement within 5km Any settlement within 2.5km	Territorial Landscape Plan of the Aosta Valley Region
Spatial Accessibility *	0 0.25 0.5 0.75 1	Lake not accessible On foot, alpinist paths On foot, excursionist paths Dirt roads/cable ways Paved roads	Open Street Map
Socio-economic value */**	0 0.33 0.67 1	Huts and services (cable ways, dams, etc.)>5km Huts and services (cable ways, dam, etc.) within 5 Km Huts and services (cable ways, dams, etc.) within 2.5 Km Huts and services (cable ways, dams, etc.) within 1 Km	Open Street Map and Territorial Landscape Plan of the Aosta Valley Region
Lake area **	0 0.5 1	103-6,297 m^2 6,297-30,257 m^2 30,257-121,220 m^2	Lake inventory
Legal Constraints *	0 1	Under protection (lake in a protected area) No protection (lake not in a protected area)	WMS of protected areas
INTERACTION WITH NATURAL INSTABILITIES			
Energy relief **	0 0.5 1	Low 427-772 m Moderate 772-1,045 m High 1,045-1,456 m	DTM
Ice and snow avalanches **	0 1	Absence in 1 km and/or interaction with human infrastructures Presence in 1 km and/or interaction with human infrastructures	Regional avalanche inventory
Rock instabilities **	0 1	Absence in 1km and/or interaction with human infrastructures Presence in 1 km and/or interaction with human infrastructures	Italian Instabilities Inventory (IFFI)

GLOF **	0 0.3 0.67 1	No interactions with any human infrastructures Interactions with paths Interactions with paths, huts, services (cable ways) Interactions with human settlement, paved roads	Lake areas DTM

Table 1. Methodology for the assessment of glacier lake values. * indicates that an interpretation by the operator was needed, ** indicates that the analysis was done automatically.

VALUE	CALCULATION
LAKE GEO-ENVIRONMENTAL VALUE (**LGEV**)	GEOMORPHOLOGICAL FEATURES + GEOLOGICAL FEATURES + HYDROLOGICAL COMPLEXITY [MAX VALUE = 3]
LAKE HUMAN ACTIVITIES AND USAGES (**LHA**)	HUMAN SETTLEMENT + SPATIAL ACCESSIBILITY + SOCIO-ECONOMIC VALUE + LAKE AREA + LEGAL CONSTRAINTS [MAX VALUE = 5]
LAKE INSTABILITIES (**LI**)	ENERGY RELIEF + AVALANCHES + ROCK INSTABILITIES + GLOF [MAX VALUE = 4]
INDEXED SINGLE LAKE VALUE (**ISLV**)	**LGEV** / 3; **LHA** / 5; **LI** / 4;
INDEXED MOUNTAIN SECTOR VALUE (**IMSV**)	MEAN **ILV LGEV** for each MOUNTAIN SECTOR; MEAN **ILV LHA** for each MOUNTAIN SECTOR; MEAN **ILV LI** for each MOUNTAIN SECTOR

Table 2. Equations used for the calculation at single lake and mountain sector scales.

Year		**2006-07**	**2015**	**Difference in number**	**Difference in %**
Number of lakes (n)	Total	169	337	+168	+99%
Elevation (m a.s.l.)	Mean	2767	2800	+33	+1%
	Max	3299	3382	+83	+2%
	Min	1820	1820	0	0%
Lake area (10^4 m^2)	Median	0.69	0.46	-0.23	-33%
	Total	116.81	155.15	+38.34	+33%
Glacier area (km^2)	Total	136.3	132.5	-3.8	-3%

Table 3. Comparison between the 2006-07 (Salvatore et al. 2015; Viani et al. 2016) and 2015 glacier lake and glacier inventories of the Aosta Valley Region.