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

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Abstract:	<p>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 km². 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.</p>
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1 **Socio-environmental value of glacier lakes: assessment in the Aosta Valley (Western Italian Alps)**

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21 ABSTRACT

22 Progressive glacier retreat can deeply impact high-mountain areas. New glacier lakes are forming and
23 potential connected opportunities (e.g. geosystem services) and risks (e.g. floods) are emerging. In the
24 last decades, glacier lakes in the European Alps have increased in number and size, including in the
25 study area (Aosta Valley Region, NW Alps, Italy). This work presents a methodology for a regional scale
26 assessment of the potential of glacier lakes for socio-environmental development of mountain
27 territories. Within the Aosta Valley, 337 glacier lakes were identified covering a total area of about
28 1.55 km². These lakes were numerically evaluated and ranked through a semi-automatic analysis in a
29 GIS environment that was based on a set of parameters related to: 1) the geo-environmental value;
30 2) the existence of human infrastructures and/or activities close to the lakes; 3) the potential
31 interaction of natural instabilities within the areas surrounding the lakes. Results showed the
32 robustness of the assessment considering some of the highest scored lakes (e.g. Lago del Miage, lakes
33 at the Rutor Glacier, etc.) and mountain sectors (Mont Blanc and Matterhorn areas). The application
34 of the proposed methodology represents an initial step towards the identification of hot-spot lakes
35 for a sustainable and integrated management, that also takes into account potential risk conditions
36 connected to natural instabilities.

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

38 **1 INTRODUCTION**

39 Ongoing climate change is deeply impacting high-mountain areas, and glacier shrinkage is one of the
40 most evident consequences. It is expected that the rapid retreat of glaciers, observed in the European
41 Alps and other mountain regions of the world, will continue in the future (Zemp et al. 2006; Hock et
42 al. 2019; Zekollari et al. 2019). The shrinkage and disappearance of glacier masses are producing
43 substantial modifications in high-mountain environments: alpine geomorphological landscapes are
44 evolving, and new landforms are developing along with new opportunities and risks (Diolaiuti and
45 Smiraglia 2010). This calls for new methodologies for assessing geomorphic changes in glacial and
46 periglacial areas (Bertotto et al. 2015). Among the newly formed landforms in recently deglaciated
47 areas, there are overdeepenings and hollows that are occupied by glacier lakes when the conditions
48 are favorable (Linsbauer et al. 2009; Buckel et al. 2018). Progressive glacier retreat is hence followed
49 by an increased number of new glacier lakes (Paul et al. 2007; Carrivick and Tweed 2013; Mergili et al.
50 2013; Emmer et al. 2014; Salerno et al. 2014; Viani et al. 2016; Laute and Beylich 2021) and by a
51 significant geomorphological evolution (disappearing, expansion/shrinkage) of the existing ones
52 (Gardelle et al. 2011; Salerno et al. 2014, 2016; Zhang et al. 2017). Along with new lake formation, also
53 the slopes in the deglaciated areas are undergoing changes, due to glacial dynamics that are gradually
54 being substituted by gravity- and water-related processes (i.e. paraglacial dynamics; Ballantyne 2002).
55 These processes can interact differently with lakes, potentially inducing hazardous situation (GAPHAZ
56 2017).
57 Among the most potentially hazardous situations there are the Glacial Lake Outburst Floods (GLOFs),
58 which are characterized by a sudden release of water from a glacier lake (Westoby et al. 2014) and
59 consequent powerful floods with high destructive potential and far-reaching impacts (Worni et al.
60 2013; Haeberli et al. 2017; Huggel et al. 2020). Among GLOFs conditioning factors, the most important
61 are: triggering mechanisms (e.g. snow and/or ice avalanches, rockfalls, rapid input of water, etc.);
62 reservoir hypsometry; geometry, composition, and structural integrity of the moraine dam (in case of
63 moraine-dammed lakes); topography and geology of the flood path (Huggel et al. 2004; GAPHAZ

64 2017). The rapid input of large volumes of material results in the formation of a displacement wave of
65 lake water which can overtop and successively breach the lake dam. Other process that can lead to
66 dam overtopping/breaching are: high-intensity rainstorm or snowmelt event, that can progressively
67 raise the lake level till the overtopping of the dam structure; piping; wastage of a buried ice-core or
68 seismic ground shaking earthquakes with connected abrupt structural failure of the moraine dam.

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

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

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

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

89 2020); moreover, glacier lakes provide water as a platform for human activity and they are basins for
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2 90 water burial and storage;
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4 91 3) *provisioning services*: lakes supply valuable material and immaterial goods for society; they are
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6 92 sources for hydropower production (Terrier et al. 2011; Purdie 2013), water reservoir (Drenkhan et al.
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8 93 2019), and tourism attractions (Purdie 2013; Wang and Zhou 2019); these services can be interpreted
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10 94 as the economic value of glacier lakes;
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12 95 4) *cultural services*: they concern the value that society gives to lakes in relation to their social meaning
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14 96 and to the importance for the community (e.g. environment quality, geotourism, cultural meaning,
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16 97 social development, research, education, and employment). Moreover, the cultural value of lakes also
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18 98 lays in their role in raising awareness about the potential hazards present in such environments (Allen
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20 99 et al. 2009; Worni et al. 2013; Emmer et al. 2015, 2016), which can hit people who are not properly
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22 100 informed (see the Lago del Miage wave in 1996 hitting people along its shore; Bollati et al. 2013).
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24 101 Numerous are the studies on the hazards connected to the presence of glacier lakes, assessed mainly
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26 102 by remote sensing techniques, topographic and geomorphometric analysis, and modelling approaches
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28 103 (e.g. Huggel et al. 2002; Bolch et al. 2011; Mergili and Schneider 2011; Schaub et al. 2013; Nussbaumer
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30 104 et al. 2014, Westoby et al. 2014; Aggarwal et al. 2016; Cook et al. 2016; Emmer et al. 2020). On the
31
32 105 other hand, there are few investigations on the services provided by glacier lakes (e.g. NELAK Project
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34 106 “New lakes in de-glaciating high-mountain areas: climate-related development and challenges for
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36 107 sustainable use” (Haeberli et al. 2013), with a particular focus on lake management considering future
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38 108 water shortages (Brunner et al. 2019; Drenkhan et al. 2019; Kellner and Brunner 2021).
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40 109 The present work aims at proposing and applying a methodology to reveal the value of glacier lakes
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42 110 from a “human perspective”, at the regional scale. Lake potentialities were assessed considering
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44 111 aspects that are important from the societal point of view and for the development of mountain
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46 112 territories. This first-order estimation is an essential basis for identifying potential “hot-spot lakes” as
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48 113 sites to prioritize for further detailed investigations aimed at their valorization, enjoyment, fruition,
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50 114 and towards their sustainable management from the socio-environmental point of view.
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116 **2 STUDY AREA**

117 The Aosta Valley (Fig. 1) is a mountainous and rather small administrative region (3,262 km²) located
118 in the Western Alps of Italy. The number of inhabitants per km² is 39, with the population mainly
119 concentrated in the valley bottom, reaching the highest density within the Aosta city (1,610
120 inhabitants per km²) (year 2015, source: www.regione.vda.it, accessed on 21st June 2021). The service
121 sector is responsible for around 80% of the regional GDP, with a very relevant role played by tourism
122 (year 2020, source: www.bancaditalia.it, accessed on 21st June 2021). In the Aosta Valley, there are
123 184 hydropower plants capable of producing a total amount of ca. 1000 MW, corresponding to ca. 5%
124 of the total hydroelectric power production in Italy (year 2019, sources: www.enelgreenpower.com,
125 www.gse.it, accessed on 21st June 2021). The elevation ranges between 321 and 4808 m a.s.l., with
126 more than 80% of the surface laying above 1500 m a.s.l. (D'Amico et al. 2020). It includes important
127 glaciated massifs such as Gran Paradiso (4061 m a.s.l.), Mont Blanc (4808 m a.s.l.), and Monte Rosa
128 (4559 m a.s.l.). The Aosta Valley is the region with the most extensive glacier cover in Italy. According
129 to the new Italian Glacier Inventory (Smiraglia et al. 2015), relative to the 2005–2011 period, in the
130 Aosta Valley Region there are 192 glaciers with a cumulative area value of 133.7 km², which
131 corresponds to 36% of the Italian glacier area. The glaciers cover an elevation ranging from about 1400
132 to 4800 m a.s.l. Considering the recent glacial withdrawal in Italy in the time period between 1959-
133 1962 and 2005-2011, the Aosta Valley has given the largest contribution (-24% of its previous area) to
134 the total national glacier loss (-30.5%) (Smiraglia et al. 2015).

135 Viani et al. (2016; 2018) reported the presence of ca. 170 glacier lakes and ponds in 2006-2007 within
136 the Little Ice Age (LIA) glacier extent in the Aosta Valley, covering an area of about 1.2 km². Seven lakes
137 with an area larger than 30,000 m² represented about 47% of the total lake coverage, but only 4% of
138 the total number of lakes. On the other hand, lakes smaller than 6,000 m² accounted for 76% of the
139 total number, but represented only the 20% of the total area. Finally, Viani et al. (2020) have modeled

140 46 potential overdeepenings (covering a total area of about 3 km²) as potential sites suitable for future
141 glacier lakes formation.

142

143 **3 DATA AND METHODS**

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

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147 **3.1 Glacier lake inventory update with respect to 2006-2007 previous inventory**

148 High-resolution aerial orthophotos were proven to be important data sources for glaciological
149 purposes (Lucchesi et al. 2013; Salvatore et al. 2015; Smiraglia et al. 2015). The Aosta Valley Region
150 and the National Agricultural Information System Agency (AGEA) performed a photogrammetric flight
151 in 2015, and the final digital orthophotos (with a spatial resolution of 0.2 m) were used as base layers
152 in an open source Geographic Information System (GIS) environment (Q-gis® 3.16). Glacier lakes with
153 a surface area greater than 100 m² were detected and their outlines were manually digitized in GIS
154 environment. The extensions of the LIA glaciers produced in the framework of the GlaRiskAlp project
155 were used as polygons in which detecting the lakes. The extensions are available as .kml file from the
156 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).

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

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

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176 **3.2 Assessment of the socio-environmental value of glacier lakes at the regional scale**

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

186 The present approach (Tab. 1) was also implemented following the methodology proposed by Bollati
187 et al. (2013; 2017 and supplementary material therein). By working at the hydrographic basin scale
188 and combining field surveys and remote sensing analyses, Bollati et al. (2013; 2017) aimed at: 1)
189 identifying potential geomorphosites; 2) evaluating these sites by applying a series of numerical
190 criteria (scientific value, additional values and potential for use, scientific index and educational index);
191 3) selecting the most suitable geomorphosites according to different purposes (scientific research,

192 education, and touristic exploitation). In Bollati et al. (2013), glacier lakes were assessed as potential
193 geomorphosites. However, the method proposed by the authors could not be applied without
194 modifications into a regional-scale study, since on-field surveys are not always possible and a more
195 automatized procedure is then required. The methodology proposed here is semi-automatic and it
196 includes some parameters detected by the operator (i.e. *Geomorphological features evidence*), and
197 other ones extracted automatically from existing vector files (i.e. instabilities and avalanches
198 inventories) and rasters (i.e. Digital Terrain Model, DTM).

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

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

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215 **3.2.1 Data sets and sources**

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

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

220 *High-resolution hillshade* - A hillshade is a grayscale 3D representation of the surface, with the sun
221 relative position taken into account for shading the image. It was obtained in GIS environment (Q-gis®
222 3.16) with the related raster function from the LIDAR-derived DTM acquired in 2008 and with a spatial
223 resolution of 2 m.

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

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

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

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

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

241 *Web Map Service (WMS) of protected areas* - The map highlights parks, natural reserves, and areas
242 belonging to the Natura 2000 Ecological Network and the habitats present on the regional territory. It

243 was published in 2016 and is available as WMS (<https://geoportale.regione.vda.it/wms/>, accessed on
1
2 244 14th April 2021).

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4 245 *DTM* - It is a LIDAR-derived DTM acquired in 2008 with a spatial resolution of 2 m.

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7 246 *Regional avalanche inventory* - It is available as a webGIS and reports the areas covered by avalanches
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9 247 identified in the period 2005-2020 (<https://mappe.partout.it/pub/geovalanghe/>, accessed on 14th
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11 248 April 2021).

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14 249 *Italian Landslide Inventory (IFFI)* - The inventory, available as shape files
15
16 250 (<https://idrogeo.isprambiente.it/app/page/open-data>, accessed on 14th April 2021), is updated to
17
18 251 2016 for the Aosta Valley Region. Each landslide is represented by a point located at the landslide
19 252 crown, by a polygon when the surface of the landslide can be mapped at the adopted survey scale
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21 253 (from 1:10,000 to 1:25,000), or by a line when the width of the landslide cannot be mapped (e.g. rapid
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23 254 debris flows).

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27 28 256 **3.2.2 Geo-environmental value**

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31 257 The geo-environmental value category includes the analysis of geomorphological, geological, and
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33 258 hydrological features characterizing the lakes. It aims at revealing lakes whose peculiarities are of
34
35 259 potential interest for the scientific community, either in term of environmental interpretation or
36
37 260 monitoring, but also for other purposes such as preservation actions of bio and/or geodiversity,
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39 261 educational activities, etc., thus providing supporting and cultural geosystem services.

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41 262 *Geomorphological features evidence* (i.e. modified from *representativeness of geomorphological and*
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43 263 *paleogeomorphological processes* in the *Scientific Value*; Bollati et al. 2017) - Geomorphological
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45 264 features may influence lake existence and evolution, in particular the characteristics of the landform
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47 265 impounding the lake (i.e. dam type). Lakes were distinguished in two classes depending on the
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49 266 presence (or absence) of evident geomorphological features impounding the lake. The assignment
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51 267 was based on the information about the dam type included in the glacier lake inventory and by
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53 268 additional investigation of the lake surroundings by visual interpretation of aerial orthophotos and/or
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269 high-resolution hillshade. Presence of evident geomorphological features (1) implies impounding by
270 lateral/frontal moraine, overdeepened bedrock, or ice. Absence of evident geomorphological features
271 (0) corresponds to a non-specific impounding (e.g. basal till, fractured bedrock). This attribute is used
272 to stress the relation between lake existence and evolution and geomorphological processes.

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

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

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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 m² in the case of the lakes considered in the present study) the

321 higher is its value for human activities (e.g. water reservoir, hydropower production, flood retention;
322 and tourism in term of lake aesthetic value).

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

327

328 **3.2.4 Interaction with natural instabilities**

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

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

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

346 *Landslides* - The presence (1) or absence (0) of landslides in the buffer area of 1 km from the lake
1
2 347 perimeter was investigated. Moreover, the interaction of slope instabilities with accessibility features
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4 348 and infrastructures reaching the lake was also taken into account.
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7 349 *GLOF - Glacier Lake Outburst Flood* - Interaction of GLOF path and run-out area with human
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9 350 infrastructures as foot paths, huts, ski lifts and cable ways, ski areas, human settlements, and main
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11 351 roads was investigated. GLOF path and run-out area were modelled following the *Gravitational*
12
13 352 *Process Path Model* (GPP model) by Wichmann (2017). The GPP model simulates gravitational
14
15 353 processes and, in particular, the movement of a mass point from an initiation site to the deposition
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17 354 area. It is a GIS-based flow-routing algorithms that can be included in the category of the simplest
18
19 355 computational models transferring flow of gravitational processes (included GLOF) sequentially
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21 356 downslope across a digital terrain model. The model is based, as Modified single-flow (MSF) models
22
23 357 adopted for GLOF simulation (Huggel et al. 2002, 2003; Allen et al. 2009), on one of the earliest,
24
25 358 simplest, and most frequently used routing method for specifying flow directions (the "D8" method
26
27 359 introduced by O'Callaghan and Mark 1984). They are relatively simple, computationally-undemanding,
28
29 360 purely raster- and DTM-based approaches for modelling downstream propagation of
30
31 361 geomorphological processes including GLOFs and are suitable for regional scale studies. The GPP
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33 362 model integrates components for process path determination, run-out calculation, sink filling, and
34
35 363 material deposition. Information about the initiation sites organized in so-called release areas,
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37 364 represented by one or more grid cells labeled as starting zones and a digital terrain model (DTM) is
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39 365 required as input data. In the present study the starting zones are represented by raster data set
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41 366 derived from lake areas, while the DTM used is the 2008 LIDAR DTM of the Aosta Valley Region.
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51 368 **3.2.5 Calculation and spatial analysis**

52 369 The scores obtained by assessing each lake according to the single parameter in the three main
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54 370 categories were used for detailed calculations provided in Tab. 2. Calculations were first performed at
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56 371 the single lake scale. Then, the results were grouped and averaged according to mountain sectors to
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372 which single lakes belong. A spatial analysis was also performed in order to determine the most
373 suitable lakes and/or mountain sectors in relation to the specific categories (e.g. geo-environmental
374 value), or even individual attributes (e.g. socio-economic value).

375

376 **4 RESULTS AND DISCUSSION**

377 **4.1 2015 glacier lake inventory and recent evolution of lake population**

378 In this study, 337 glacier lakes were identified, with a total area of $155.15 (\pm 0.82) \times 10^4 \text{ m}^2$ (median
379 $0.46 \times 10^4 \text{ m}^2$). Lakes areas varied between a minimum of about $0.01 \times 10^4 \text{ m}^2$ to a maximum of $12 \times$
380 10^4 m^2 . Approximately 67% of the lakes were characterized by an area smaller than $0.2 \times 10^4 \text{ m}^2$ and
381 84% of the lakes had a surface area less than $0.6 \times 10^4 \text{ m}^2$. The elevation ranged between 1820 and
382 3382 m a.s.l. (mean value: 2800 m a.s.l.). In the year 2015, 70% of the lakes were located between
383 2600 and 3000 m a.s.l. According to mountain sectors (Fig. 1), glacier lakes of the 2015 inventory were
384 localized mainly in the Rutor-Lechaud (30%), Gran Sassièrè-Tsanteleina (16%), Bouquetins-Cervino
385 (12%), and Monte Rosa (12%). The geographic distribution of the glacier lakes was similar to those of
386 the 2006-2007 inventory for the first two most lake-populated mountain sectors that were followed
387 in the previous inventory by the Monte Rosa and the Gran Paradiso. They were mainly proglacial lakes
388 impounded by bedrock (fractured bedrock - 32% or evident bedrock overdeepenings - 12%), basal
389 debris (41%), or moraine (11%). There were also a few cases of ice-dammed lakes (4%). As mentioned
390 in similar studies (e.g. Emmer et al. 2020), also for the Aosta Valley glacier lakes there is the evidence
391 of a transition from moraine-dammed lakes (dammed by the LIA moraines) already existing in the
392 oldest inventories (Viani et al. 2016; 2018), to bedrock-dammed lakes (impounded by fractured
393 bedrock or by bedrock overdeepenings). This last type of lake is becoming predominant, including also
394 lakes impounded by basal debris potentially covering a bedrock dam.

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

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

398 - the total area increased of ca. 30% (with an annual rate of ca. 0.04 km²/yr of new lake area);
399 - the mean elevation raised because of new lakes in recently deglaciated areas left by glaciers at
400 progressively higher elevation;
401 - the mean area decreased because of a large amount of newly formed small lakes in areas recently
402 exposed by small ice body (<0.5 km²) that are predominant (ca. 84%). Moreover, according to the type
403 of classification, the majority are mountain glaciers and glacierets (according to Smiraglia et al. 2015),
404 which are not characterized by large tongues with thick ice, that are the conditions for the presence
405 of large overdeepenings;
406 - glaciers lost 3% of their surface.
407 Considering the number of new lakes per year, a similar result (19 lakes/yr) has been shown by Mölg
408 et al. (2021) in Switzerland, for a comparable time period (2006-2015). The calculated new annual lake
409 area was about the quadruple (0.15 km²/yr) with respect to the Aosta Valley. In Austria, Buckel et al.
410 (2018) found a lower number of lakes per year (6.5), although the new annual lake area was double
411 (0.08km²/yr) with respect to the present study. Considering the mean elevation of glacier lakes, the
412 value found in the Aosta Valley (2800 m a.s.l.) was higher with respect to both Switzerland and Austria,
413 which showed similar elevations (ca. 2600 m a.s.l.).
414 The increase in lake number and area that has occurred in the most recent decade (from 2006 to 2015)
415 is the strongest, considering the entire XX and beginning of XXI centuries (Viani et al. 2016). Similar
416 results emerged from Mölg et al. (2021), who found an exceptionally strong increase of glacier lakes
417 from 2006 to 2016 in Switzerland. Similarly, a sudden increase in lake number and area over the most
418 recent decade (2006-2015 period) was found by Buckel et al. (2018) in Austria.
419 Considering the exposed area due to glacier retreat since the Little Ice Age (193 km²) with respect to
420 the total area covered by glacier lakes in 2015 (1.55 km²), 0.8% of the deglaciated area was occupied
421 by lakes. A similar result, ca. 0.9%, was found by Mölg et al. (2021) in Switzerland (deglaciated area:
422 740 km² of deglaciated area; area occupied by lakes: 6.22 km²) while, in Austria, Buckel et al. (2018)
423 showed a lower percentage of ca. 0.5% (deglaciated area: 613 km²; area occupied by lakes: 2.93 km²).

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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).

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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 m² 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 Sassièra-Tsanteleina, Rhêmes Valley). As the previous one, it is a very large lake of about 95,000 m² 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

1 et al. (2021). These lakes were also included in a wider lake population, with the neighboring lakes of
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3 451 the Long-Term Ecological Research Network (LTER), in order to understand the contribution of the
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5 452 glacier melt water to the chemical composition of the water of the lakes, compared to lakes that are
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7 453 not fed by glaciers (Colombo et al. 2019b). A high score was obtained also by the Lago del Miage. The
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9 454 Lago del Miage (Monte Bianco, Veny Valley) is of considerable significance for both scientific and
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11 455 touristic interest (Deline et al. 2004; Diolaiuti et al. 2006, 2017; Bollati et al. 2013, 2015). The lake has
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13 456 existed since the XVIII century. Deline et al. (2004) reported that several drainage events took place
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15 457 between 1930 and 1990. In particular, the authors analyzed the event occurred in September 2004,
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17 458 when the lake area was 36,000 m² and the depth was 30 m. Diolaiuti et al. (2006) described rates,
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19 459 processes, and morphology of freshwater calving at Miage Glacier into the Lago del Miage. Finally, the
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21 460 lakes at Balanselmo, Dragone and South-West Château des Dames glaciers (Bouquetins-Cervino,
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23 461 Valtournenche Valley) are worth mentioning. These lakes are located in evident bedrock
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25 462 overdeepenings, connected to each other, and influenced by the presence of structural features
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27 463 crossing the area from SW to NE (Fig. 5b).
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35 465 *4.2.2 Interaction with human activities and usages*

37 466 The highest score (0.9) related to the presence of human activities in its proximity was achieved by
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39 467 the first formed lake in the proglacial area of the Rutor Glacier after the end of the LIA (Rutor-Lechaud,
40
41 468 La Thuile Valley). The Lago del Rutor (Fig. 5c) is the third largest lake in the Aosta Valley in terms of
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43 469 lake area (ca. 103,000 m²). It is located in a highly frequented area that is reached by an important
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45 470 excursionist path (Alta Via n. 2) and logistically supported by the presence of the Deffeyes Hut.
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49 471 The second lake (score: 0.83) is the Gran Lago (previously mentioned for its high LGEV score). The lake
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51 472 is located at the South-West Château des Dames Glacier and it covers about 61,000 m² (Bouquetins-
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53 473 Cervino, Valtournenche Valley). The lake presents an artificial dam on the south side and, according
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55 474 to the Aosta Valley lake inventory, part of the water of the outflow is collected by a pipe.
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1 475 The third ranking lake (score: 0.82) is one of the Cime Bianche lakes located in the proglacial area of
2 476 the Valtournenche Glacier (Bouquetins-Cervino, Valtournenche Valley), with an extent of about
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4 477 107,000 m² (Fig. 5d). Its outflow is partially channeled because of the presence of a dirt road crossing
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6
7 478 the drain path. The area presents several infrastructures, including artificial dams connected to ski
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9 479 activities.

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11 480

14 481 *4.2.3 Interaction with natural instabilities*

16 482 This category represents a limit to the potentialities of lakes related to possible risk conditions
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19 483 (Haeberli et al. 2017).

21 484 The Eastern Morion Glacier (Rutor-Lechaud, Valgrisenche Valley) presents several moraine-dammed
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23 485 lakes positioned on a rocky step. The lakes show different colors on the aerial orthophotos and the 3D
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25
26 486 images from Google Earth; this is probably due to the different sources of the water filling them
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28 487 (melted glacier ice or precipitation). Marcello and Meda (2013) reported “water drainage and water
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31 488 channeling that overflowed the Lakes of Morion, forming waterfalls”. These characteristics granted
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33 489 them a high geo-environmental value (1). Moreover, the presence in their proximity of the Angeli di
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35 490 Morion Hut and the passage of the Alta Via n. 2, one of the most famous excursionist routes in the
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38 491 Aosta Valley Region, also gave them a high value connected to the presence of human activities (0.7).
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40 492 The same lakes reached the highest scores (above 0.8) with respect to the presence of different
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42 493 potential instabilities affecting the area, in particular the sinking phenomena affecting the paths
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45 494 reaching the lakes. Moreover, the GLOF model shows that the area affected by a potential outburst
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47 495 flood could interact with the paths and the paved road in the main valley, generating potential risk
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50 496 conditions (Fig. 5e).

52 497 High value (0.92) connected to the presence of potential instabilities was found for the lake at the
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54 498 Frebouzie Glacier (Monte Bianco, Veny Valley). In fact, in 2002 the Frebouzie Glacier was affected by
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57 499 an ice avalanche detached from the glacier front, falling for about 400 m on the steep rock step (Deline
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1 et al. 2002; 2004. Fig. 5f). This has to be taken into account, especially now, given the presence of the
2 lake.
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6 7 503 **4.3 Mountain sector assessment**

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9 504 The analysis performed on single lakes can also be applied aggregating the lakes according to the main
10 mountain sectors of the Aosta Valley Region. The indexed mountain sector values (Fig. 6), ranging
11 505 from 0 to 1 highlights the different performance of the lakes of the different mountain sectors.
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15 507 Considering the geo-environmental value, the mountain sector showing the highest score is the Mont
16 Blanc (0.77). This sector has fewer lakes (18) than the other ones in the region, although it includes
17 the majority of the ice-dammed lakes in the study area (8), those located on the surface of the debris-
18 covered Miage Glacier, and the well-known and well-studied Lago del Miage and Lago del Giardino del
19 Miage (cf. Bollati et al. 2013; 2015). Moreover, values above the mean were observed for the two
20 neighboring mountain sectors Lusency-Cian (0.71) and Bouquetins-Cervino (0.58). Indeed, they
21 include the above-mentioned lakes at Balanselmo, Dragone, and South-West Château des Dames
22 glaciers (Valtournenche Valley); these lakes are located in evident bedrock overdeepenings,
23 connected to each other, and influenced by the presence of structural features crossing the area from
24 SW to NE. The numerous lakes in the Breuil basin above the hamlet of Breuil-Cervinia are also included.
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26 511 According to these peculiar characteristics, they could be of interest for the scientific community
27 focusing on the causes of the formation of glacier lakes and, more in general, on the emerging
28 landforms in enlarging proglacial areas.
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32 513 The mountain sector that shows the highest score related to the presence of glacier lakes (e.g. those
33 in the proglacial area of the Valtournenche Glacier) close to human activities is the Bouquetins-Cervino
34 (0.59). Bouquetins-Cervino is the third mountain sectors considering the number of glacier lakes (40)
35 and it has important tourist centers like Breuil-Cervinia, ski resorts as well as artificial dams used for
36 hydropower and snow production.
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2 525 Regarding potential interactions of natural instabilities with the lakes and the surrounding areas, the
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4 526 mountain sector with the highest score is the Mont Blanc (0.62). This sector includes the above
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6 527 mentioned Frebouzie Glacier as well as the Triolet Glacier. The latter was affected in 1717 by a
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8 528 historical collapse of rock and ice that moved down the valley for about 7 kilometers (Porter and
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10 529 Orombelli 1980). Moreover, slopes of this sector are characterized by a high energy relief that can
11
12 530 influence the activation and/or propagation of natural instabilities like outburst floods from glacier
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14 531 lakes. In fact, the GLOF modeled in the present study shows the flood path potentially reaching the
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16 532 valley bottom where a dirt road and an excursionist path are present.
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21 534 **4.4 Advantages, limits, and possible implementations of the applied methodology**

22 23 535 **4.4.1 Advantages**

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26 536 The present study aimed at identifying (by updating the glacier lake inventory) and selecting (by the
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28 537 application of the approach for lake socio-environmental value assessment) sites to be prioritized for
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30 538 valorization, enjoyment, fruition, and sustainable management from a socio-environmental point of
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32 539 view. The selection of elements was based on a numerical assessment including several parameters
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35 540 to which different scores were assigned to decrease the subjectivity associated with any evaluation
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38 541 procedure, as recommended for geosites (i.e. lakes) (Brilha, 2016). Following Brilha (2016), the
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40 542 assessment was performed at the regional scale and on dozens of sites for which the assessment
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42 543 reasonably provides more robust results than for a limited area and reduced number of sites.
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45 544 Moreover, Bruschi et al. (2011) showed that a high number of criteria does not necessarily imply a
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47 545 more accurate assessment, thus the selection was done according to the most representative ones
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50 546 for each of the three categories. Finally, a concluding reflection on the quality of the numerical results
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52 547 is essential by experts adopting the present approach. It has to be based on the knowledge of the
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54 548 context acquired directly by field surveys and indirectly by existing literature, in order to confirm the
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57 549 results and search for eventual invalid ranking positions (Brilha 2016). The subjectivity inherent to an
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59 550 assessment of geosites cannot be totally eliminated. However, the approach proposed in the present
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1 551 study can surely decrease some of this subjectivity that, in any case, is considered secondary with
2 552 respect to the primary need of obtaining a sorted list of sites on which basing potential future
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4 553 management strategies.

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7 554 The robustness of the results obtained from the application of the proposed methodology is confirmed
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9 555 by the fact that the value of several high-scored lakes has already been recognized by society. For
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11 556 instance, numerous lakes showing high geo-environmental values are already known among the
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13 557 scientific community and have been the subject of several studies (e.g. lakes at Tzére, Indren, and
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15 558 Miage glaciers). Moreover, some of the lakes with high values, according to the interaction with
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17 559 human activities and usages, are well established tourist destinations (e.g. Lago del Miage and lakes
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19 560 at the Rutor Glacier). Thanks to the results of this assessment, some highly interesting cases emerged
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21 561 from lakes that are not well known, and could be studied. For instance, the lakes at the Balanselmo,
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23 562 Dragone, and South-West Château des Dames glaciers, where a complex of geological and
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25 563 geomorphological features interact and influence lake conformation and position, are an ideal didactic
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27 564 example of high-mountain geodiversity.
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34 35 566 4.4.2 Limits

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38 567 The limits of this approach are linked to its presuppositions. Indeed, the method is designed in order
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40 568 to be semi-automatic and applicable at the regional scale. Some aspects like the potential ecologic
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42 569 support role of the lakes, as well as their cultural value, emerged as important characteristics that
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44 570 require deep consideration. They are fundamental geosystem services, however, despite their
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46 571 importance, they are difficult to be evaluated without an extensive survey. For example, the previously
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48 572 mentioned Lago Goletta, which shows a high geo-environmental value, was analysed by Tiberti et al.
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50 573 (2020), who recognized its ecological value related to the biotic main features (i.e. picocyanobacterial
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52 574 abundance). This characteristic was assessed as ecological support role in the scientific value frame
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54 575 for geomorphosites by Bollati et al. (2013; 2017), and it falls into the supporting geosystem service as
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56 576 proposed by Gray (2013). It is considered fundamental to assess a geomorphosite (Bollati et al. 2015),
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1 577 but this requires detailed case-by-case evaluation, which is not feasible at the regional scale. An
2 578 attempt to partially consider the importance of lakes for the natural ecosystem is represented by the
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4 579 “Hydrological complexity” parameter although a further implementation is recommended.

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7 580 Another example of characteristics that require deep consideration is represented by the lakes in the
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9 581 area of the Rutor Glacier. The area includes the Lago Santa Margherita (a lake outside the LIA glacier
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11 582 extent and thus not considered in the inventory and in the assessment). This lake is famous for the
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13 583 several GLOFs occurred between 1430 AD and 1864 AD due to glacier front fluctuations that caused
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15 584 much damage and many fatalities (Dutto and Mortara 1992; Orombelli 2005). Due to these events,
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17 585 religious processions were made to the area; later, in 1937, a chapel was built on a promontory on the
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19 586 lake as a devotional place to bring an end to the devastating outburst floods, and every year a Mass is
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21 587 celebrated. This aspect could be assessed as a cultural value of geomorphosites (Bollati et al. 2017),
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23 588 that considers the material and immaterial traditions linked to the site, and it is part of the cultural
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25 589 geosystem service proposed by Gray (2013). The cultural value was not considered in the present
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27 590 study since the proposed methodology needs a complete regional database of the analyzed
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29 591 parameters that is not available for cultural elements, as well as for the ecological value. These two
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31 592 aspects, in fact, assume a deep knowledge of the single lakes and of their related territory. Potentially,
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33 593 they could be evaluated for the high-scored lakes, with ad-hoc field surveys that could be conducted
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35 594 to collect further data.

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38 595 The newly formed lakes are appearing and changing continuously, hence this relatively fast running
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40 596 and semi-automatic procedure could represent an ideal tool available to local administrators for
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42 597 periodic review of the status of glacier lakes, and of their value. A change in their conditions, for both
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44 598 natural or human-induced causes, can mine their values (Pelfini and Bollati 2014) and influence also
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46 599 the geodiversity of such dynamic contexts (Zwolinski 2009). The re-run of such analysis will be possible
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48 600 if the input data are periodically updated, especially the glacier lake inventories (derived from aerial
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50 601 orthophotos). Considering the other input data, it has to be taken into account that some of them may
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52 602 be outdated. In the present study, information sought from the Territorial Landscape Plan of the Aosta
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603 Valley Region was used. It consists of texts, sheets, and maps with related downloadable shape files
604 related to the situation in 1998 without subsequent updates. This is a limit to the use of the dataset
605 because of important modification that can have taken place in the meantime on the regional
606 territory. However, this is the only official information regarding human infrastructures and
607 settlements. Updated information can be sought via OpenStreetMap that provides downloadable
608 shapefiles. In this case, being the information of OpenStreetMap based on the concept of Volunteered
609 Geographic Information (VGI), the data quality depends on the balance between contributors'
610 freedom and their respect of specifications (Girres and Touya 2010). The outdated but officially
611 approved information provided by the Territorial Landscape Plan of the Aosta Valley can be verified
612 and integrated by the updated but heterogeneous data of OpenStreetMap.

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

626 4.4.3 Potential implementations

627 The methodology proposed in the present study aims at considering and integrating different aspects
628 that characterize glacier lakes. The goal of the present approach is not to propose specific methods

629 for the elaboration of single parameters needed for the assessment. Indeed, if dedicated researches
1
2 630 already exist on specific features, their results could merge into this comprehensive analysis, also
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4 631 extending its application to other mountain regions. This is particularly evident for studies on regional
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6 632 GLOF assessments that cover the main mountain regions of the world (e.g. Allen et al. 2019; Emmer
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8
9 633 et al. 2020). Finally, since there are inventories of potential future lakes in several mountain areas of
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11 634 the world (e.g. Magnin et al. 2020; Viani et al. 2020), it would be interesting to investigate the potential
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14 635 of future lakes as sources of geosystem services for society.

15
16 636 The application of the proposed methodology represents an initial step towards the identification of
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19 637 hot-spot lakes to be sustainably managed for a number of purposes like geoscience education,
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21 638 landscape protection, nature conservation, tourism attraction, hazard mitigation, water reservoir for
22
23 639 mountain huts, and artificial snow and/or hydropower production. The mentioned purposes can be in
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25
26 640 synergy and/or in conflicts, as underlined by Haeberli et al. (2016). For example, multipurpose projects
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28 641 for hazard mitigation by flood retention, hydropower, and water reservoir can be implemented
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30
31 642 generating potential synergies. In contrast, projects that imply the construction of infrastructures may
32
33 643 be in strong conflict with the presence of protected natural areas and landscape. Synergies and/or
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35 644 conflicts can also emerge when lakes present hazardous conditions: they can reduce the
36
37
38 645 attractiveness of the territories where the lakes are located because of the connected risk; on the
39
40 646 other hand, they may also enhance the visibility and thus the frequentation (e.g. Lago Effimero on the
41
42 647 east face of the Monte Rosa Massif; Mortara and Mercalli 2002). The comprehensive matrix-type
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44
45 648 approach proposed by Haeberli et al. (2016) can be applied to single cases for a first evaluation of
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47 649 these aspects. Moreover, surveys with tourists and local populations on their perception of the
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50 650 different values of glacier lakes could be proposed and performed. Finally, proper communication to
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52 651 decision makers and stakeholders (i.e. usable science; Giordan et al. 2015) has to be favored in order
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54 652 to promote integrative/participative planning and management of lakes at all levels.

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58 59 654 **5 CONCLUSION**

1 655 The application of the proposed methodology aims at identifying (by updating the glacier lake
2 656 inventory) and selecting (by applying the approach for lake socio-environmental value assessment)
3
4 657 lakes to be prioritized for sustainable management strategies. Hundreds (337) of glacier lakes were
5
6 658 identified in the Aosta Valley region, covering a total surface of about 1.55 km² (0.05% of the entire
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8 659 region). In 2015, glaciers lost 3% of their surface with respect to the 2006-2007 inventory, while the
9
10 660 total number of lakes doubled and their area increased of approximately 30%. These newly formed
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12 661 glacier lakes have undergone a semi-quantitative assessment of their socio-environmental value in
13
14 662 order to obtain a ranking list. Those performing the highest scores were then evaluated based on
15
16 663 information acquired directly by field surveys and indirectly by existing literature. Results showed the
17
18 664 robustness of the assessment considering some of the highest scored lakes (e.g. Lago del Miage, lakes
19
20 665 at Rutor Glacier, etc.) and mountain sectors (Mont Blanc and Matterhorn areas).
21
22 666 The proposed assessment facilitates the determination of the most promising lakes and related
23
24 667 territories for potential sustainable development by dedicated projects (e.g. educational, tourism,
25
26 668 geoconservation, etc.) taking into account possible emerging synergies and conflicts. Information
27
28 669 about the interaction of the lakes and surrounding areas with natural instabilities provides a rationale
29
30 670 for excluding sites in relation to potential risk conditions and, in turn, selecting those that provide
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32 671 benefits without risks.
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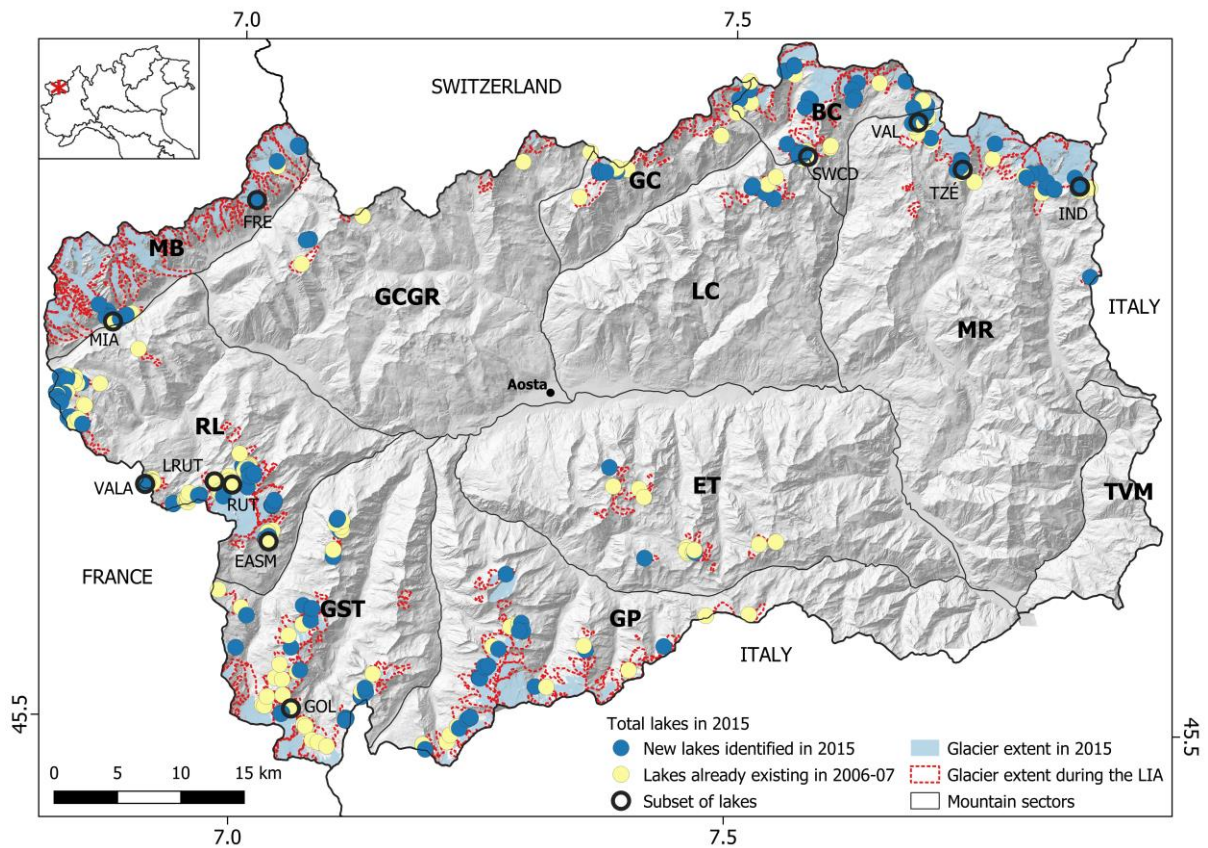


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Editor	
Comment	Response
Reviewer #1	
<p>The two reviewers have now commented on your revised paper. After consideration, the editor Professor Helmut Haberl and I invite you to undertake a minor revision of your manuscript.</p>	<p>We thank the editors 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.</p>
<p>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.</p> <p>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.</p> <p>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).</p> <p>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.</p> <p>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.</p>	<p>We thank the reviewer for the valuable comments that helped us to improve the previous manuscript.</p>
<p>However, I still have some minor comments, most of which regard the newly added GLOF explanatory paragraph (L57-66):</p>	<p>All comments have been addressed, providing an item-by-item response to each comment as it can be read in our responses below.</p>
<p>L57-58 and L64-66: Consider merging these two sentences into one.</p>	<p>L57-60 Amended</p>
<p>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.</p>	<p>L62 Amended</p>
<p>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.</p>	<p>L65-68 We agree with the reviewer about adding this additional information. We modified the sentence accordingly</p>
<p>An additional minor comment refers to the Figure 5's caption (L38): What is "sky</p>	<p>L40 Agreed and amended.</p>

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<p>tourism"? Based on this paper's context I guess that you mean "ski tourism".</p>	
<p>Reviewer #2</p>	
<p>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.</p>	<p>We thank the reviewer for the valuable comments that helped us to improve the previous manuscript.</p>
<p>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.</p>	<p>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").</p>
<p>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.).</p>	<p>L262-272 We modified the paragraph related to the <i>Geomorphological features evidence</i> 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.</p>
<p>Additional modification</p>	<p>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 white with the actual version in colors.</p>



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2 Figure 1. Map of the study area showing: the glacier extent during the LIA and in the year 2015;

3 glacier lakes identified in 2015, separating new lakes firstly recognized in 2015 (blue dots) and lakes

4 already existing in the previous inventory of 2006-2007 (yellow dots). Bold circles with associated

5 abbreviations indicate a subset of specific lakes mentioned in the paper: Indren (IND), Tzère (TZÉ),

6 Valtournenche (VAL), South West Château des Dames (SWCD), Frebouzie (FRE), Miage (MIA),

7 Valaisan (VALA); Lago del Rutor (LRUT), Rutor (RUT), Eastern Morion (EASM), Goletta (GOL).

8 Mountain sectors (abbreviations in bold in the map) are: Monte Rosa (MR), Bouquetins-Cervino (BC)

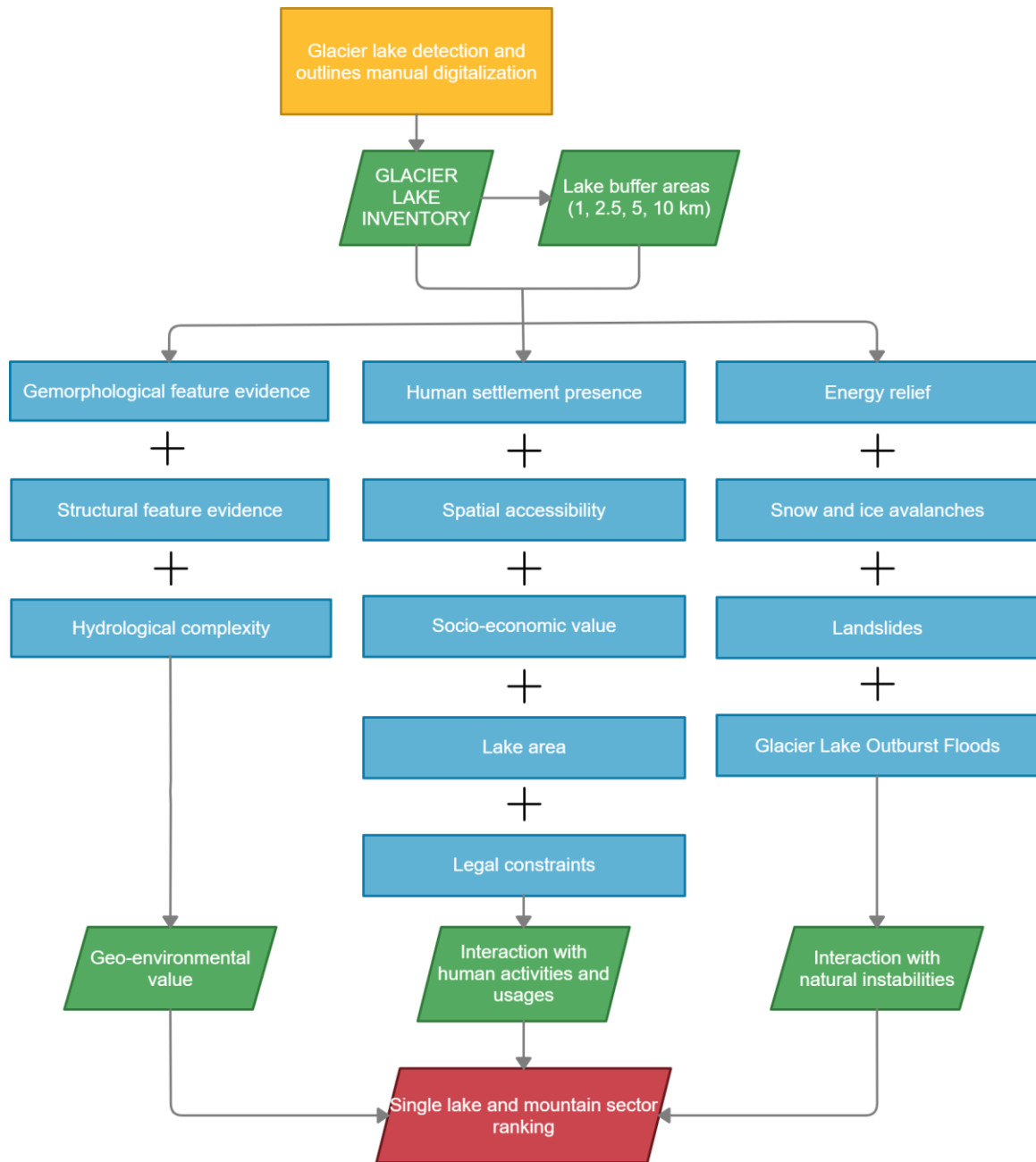
9 also named Matterhorn, Luseny-Cian (LC), Gelé-Collon (GC), Grand Combin-Mont Velan + Grande

10 Rochère-Grand Golliaz (GCGR), Dolent-Argentièra-Trient + Monte Bianco + Trélatête (MB) also

11 named Mont Blanc, Rutor-Lechud (RL), Gran Sassièra-Tsanteleina (GST), Gran Paradiso + Rosa dei

12 Banchi (GP), Emilius-Tersiva (ET), and Tre Vescovi-Mars (TVM). The base map is the hillshade derived

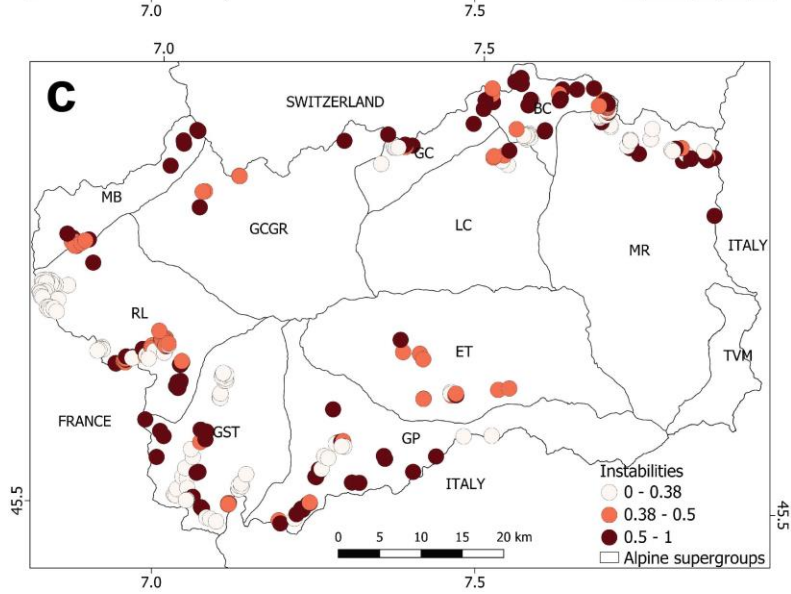
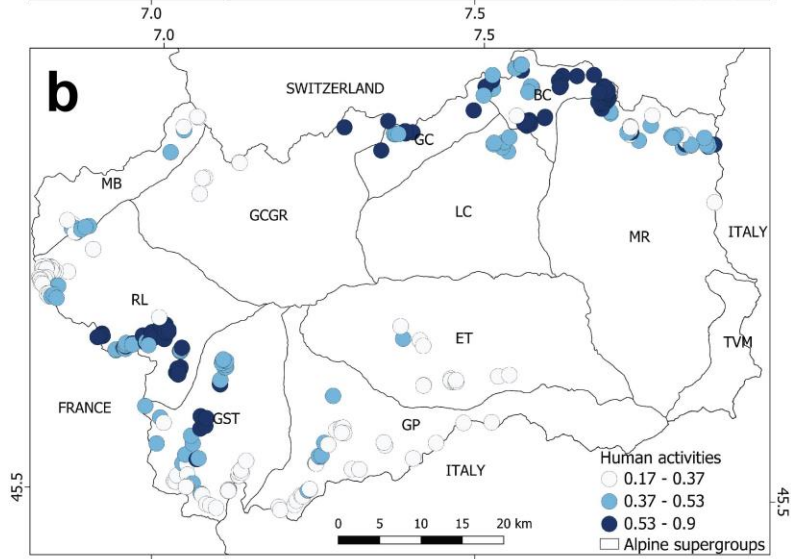
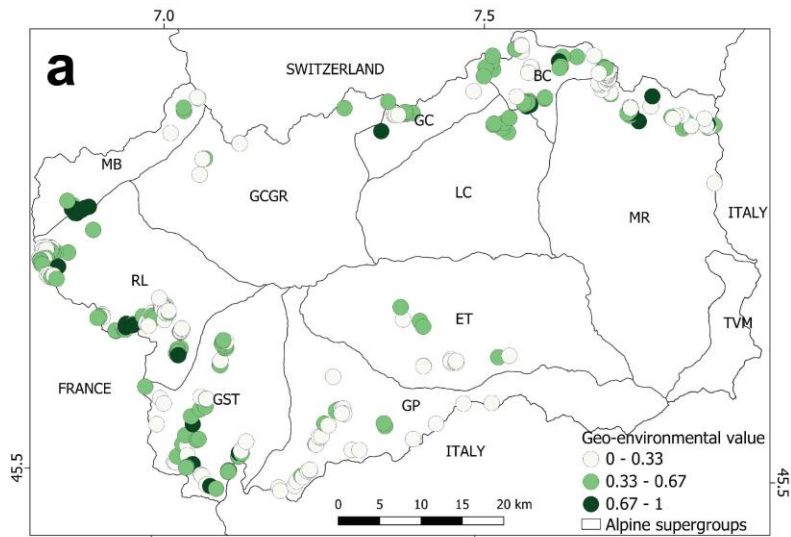
13 from 2008 LIDAR DTM of the Aosta Valley Region.



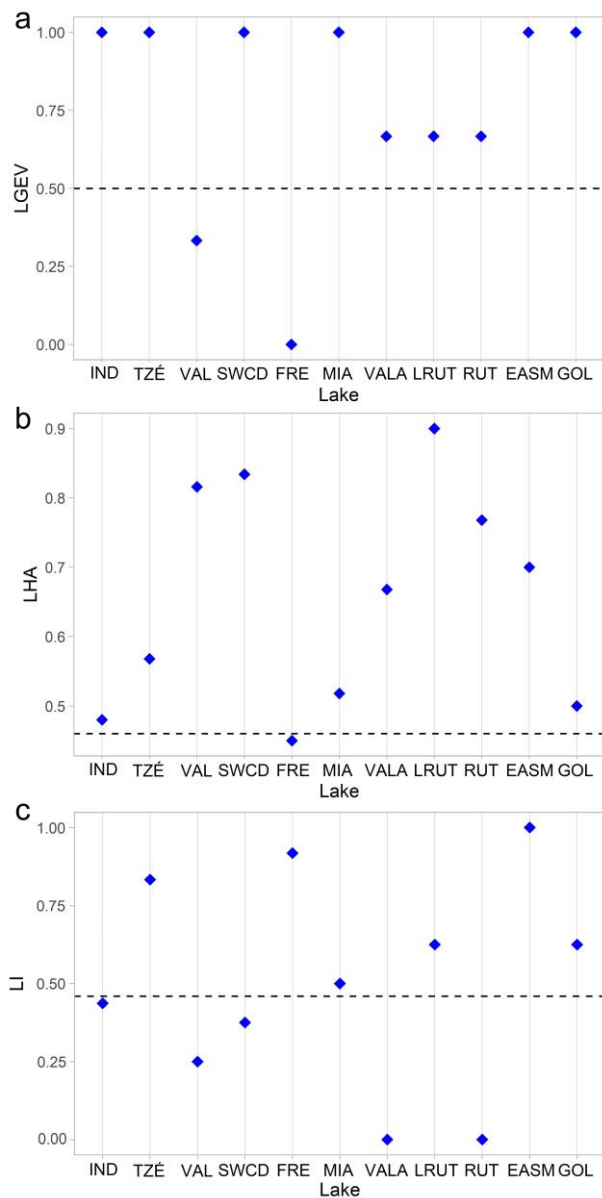
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15 Figure 2. Flowchart of the overall methodological approach adopted in the present study.

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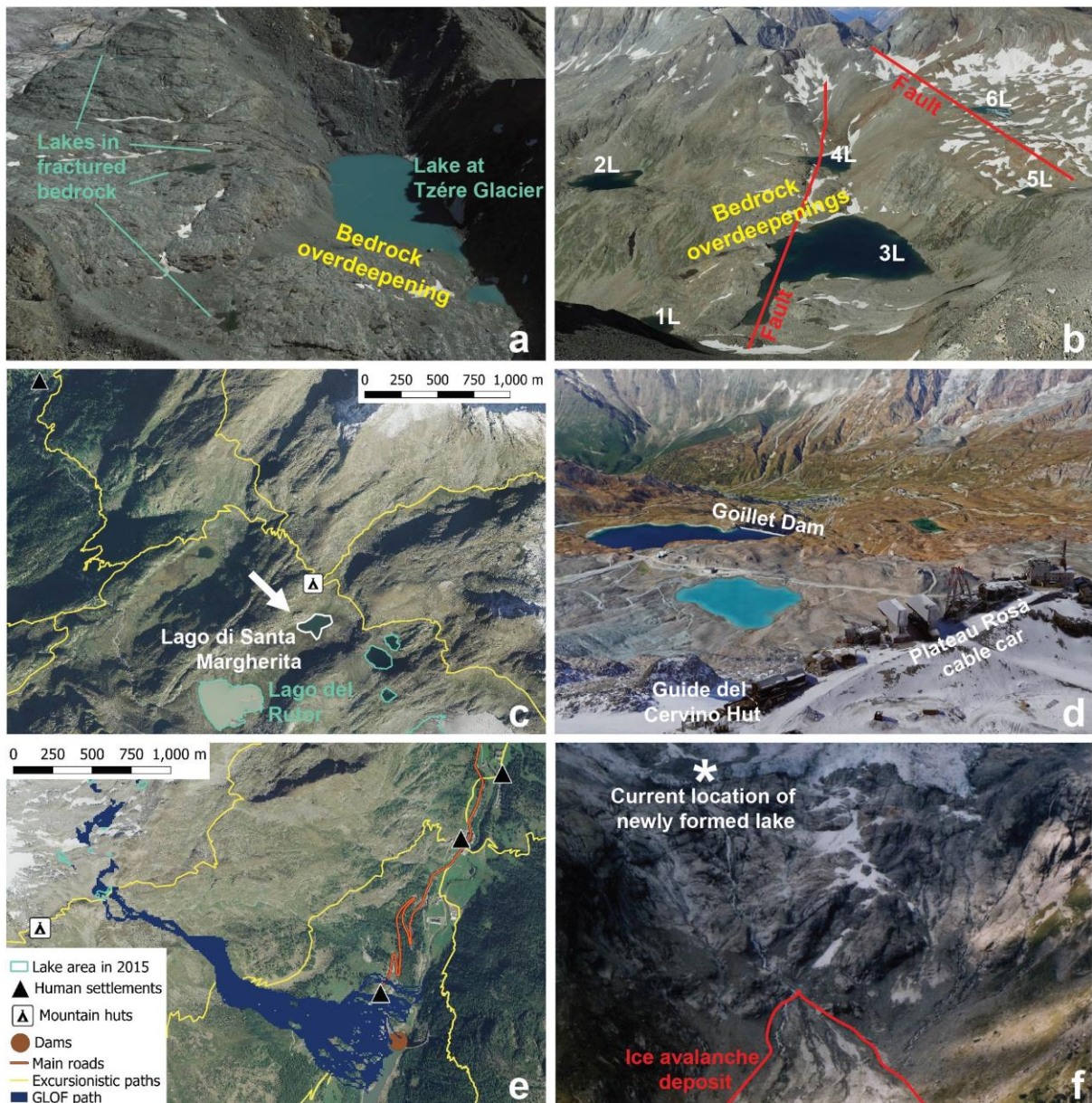


18 Figure 3. Maps showing the results obtained by single lakes according to: a) geo-environmental value
19 (LGEV), b) human activities (LHA) and, c) instabilities (LI). Abbreviations refer to mountain sectors
20 reported in the caption of Fig. 1.



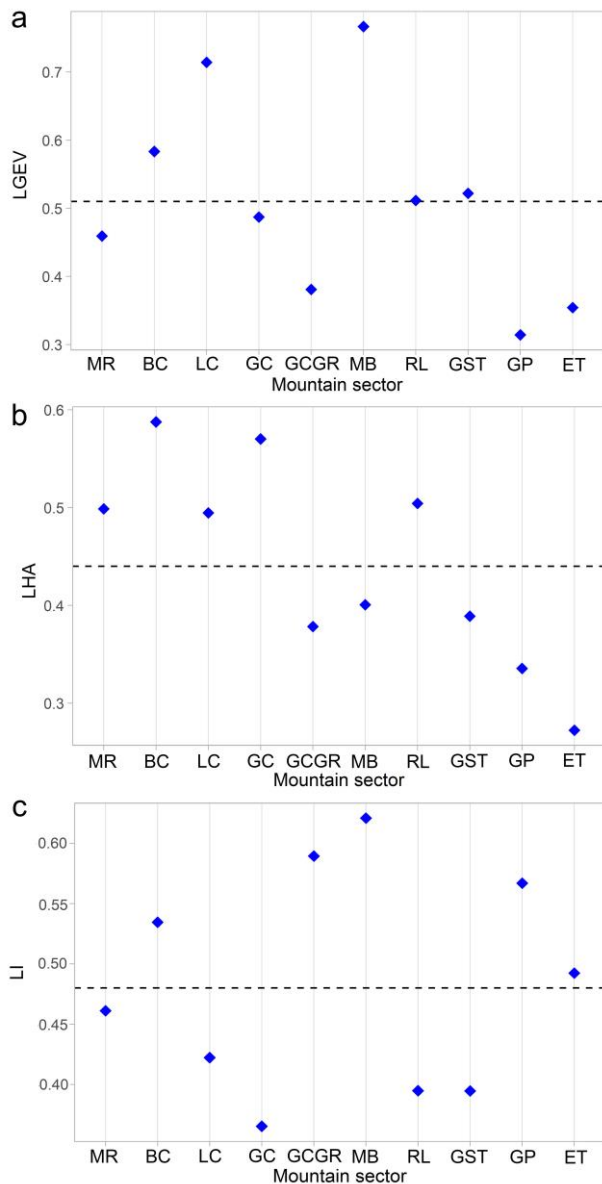
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22 Figure 4. Indexed single lake value (ISLV) (blue rhombi) for a) geo-environmental value (LGEV), b)
 23 human activities (LHA), and c) instabilities (LI) for the subset of lakes that separately showed highest
 24 indexed value with respect to the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



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

40 exploitation for ski tourism (3D image from Google Earth dated after 2016). Interaction with natural
41 instabilities: e) lakes at the Eastern Morion Glacier on the rock step facing on the Valgrisenche Valley
42 (EASM, RL). Paved road and other human infrastructures in the valley floor are present (basemap
43 2006 orthophoto, source Geoportale Nazionale); f) deposit of the ice avalanche detached from the
44 Frebouzie Glacier in 2002 (photo from Deline et al., 2002) and current location of the newly formed
45 lake* (FRE, MB).



46

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

GEO-ENVIRONMENTAL VALUE			
<i>Parameter</i>	<i>Value</i>	<i>Description</i>	<i>Data sources</i>
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	No interactions with any human infrastructures	Lake areas DTM
	0.3	Interactions with paths	
	0.67	Interactions with paths, huts, services (cable ways)	
	1	Interactions with human settlement, paved roads	

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 (LGEV)	GEO-ENVIRONMENTAL VALUE	GEOMORPHOLOGICAL FEATURES + GEOLOGICAL FEATURES + HYDROLOGICAL COMPLEXITY [MAX VALUE = 3]
LAKE (LHA)	HUMAN ACTIVITIES AND USAGES	HUMAN SETTLEMENT + SPATIAL ACCESSIBILITY + SOCIO-ECONOMIC VALUE + LAKE AREA + LEGAL CONSTRAINTS [MAX VALUE = 5]
LAKE (LI)	INSTABILITIES	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.