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# 1 Use of multi-criteria decision analysis to identify potentially dangerous glacial 2 lakes

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15 Decision theory, Multi-criteria decision analysis (MCDA)

## 16 Abstract

17 Glacial Lake Outburst Floods (GLOFs) represent a significant threat in deglaciating environments,  
18 necessitating the development of GLOF hazard and risk assessment procedures. Here, we outline a  
19 Multi-Criteria Decision Analysis (MCDA) approach that can be used to rapidly identify potentially  
20 dangerous lakes in regions without existing tailored GLOF risk assessments, where a range of glacial  
21 lake types exist, and where field data are sparse or non-existent. Our MCDA model (1) is desk-based  
22 and uses freely and widely available data inputs and software, and (2) allows the relative risk posed  
23 by a range of glacial lake types to be assessed simultaneously within any region. A review of the factors  
24 that influence GLOF risk, combined with the strict rules of criteria selection inherent to MCDA, has  
25 allowed us to identify 13 exhaustive, non-redundant, and consistent risk criteria. We use our MCDA  
26 model to assess the risk of 16 extant glacial lakes and 6 lakes that have already generated GLOFs, and  
27 found that our results agree well with previous studies. For the first time in GLOF risk assessment, we  
28 employed sensitivity analyses to test the strength of our model results and assumptions, and to  
29 identify lakes that are sensitive to the criteria and risk thresholds used. A key benefit of the MCDA  
30 method is that sensitivity analyses are readily undertaken. Overall, these sensitivity analyses lend  
31 support to our model, although we suggest that further work is required to determine the relative  
32 importance of assessment criteria, and the thresholds that determine the level of risk for each  
33 criterion. As a case study, the tested method was then applied to 25 potentially dangerous lakes in

34 the Bolivian Andes, where GLOF risk is poorly understood; 3 lakes are found to pose ‘medium’ or ‘high’  
35 risk, and require further detailed investigation.

## 36 **1. Introduction**

37 Glaciers in most parts of the world are receding and thinning in response to climate change (Zemp et  
38 al., 2015). Glacier recession into rock basins and behind moraines leads to the ponding of meltwater  
39 as proglacial lakes (e.g. Carrivick and Tweed, 2013; Cook and Quincey, 2015), and glacier thinning  
40 results in the development of supraglacial lakes, particularly on debris-covered glaciers (e.g. Benn et  
41 al., 2001; Thompson et al., 2012; Mertes et al., 2016). Consequently, there has been a general trend  
42 of increasing glacial lake number and size in many regions in recent times (e.g. Carrivick and Tweed,  
43 2013). Glacial lake outburst floods (GLOFs) may occur where the impounding dam (ice, rock, moraine,  
44 or combination thereof) is breached or overtopped. Thousands of people have lost their lives to such  
45 events in the last few decades, mostly during the 1941 GLOF at Huaraz, Peru, and the 2013 Kedernath  
46 event, India (Richardson and Reynolds, 2000; Allen et al., 2015; Carrivick and Tweed, 2016). Given the  
47 risk posed to downstream communities, industry and infrastructure in deglaciating mountain ranges  
48 worldwide, there has been an intensification of research interest in GLOFs (Emmer and Vilímek, 2013),  
49 with many such studies seeking to estimate GLOF hazard or risk for individual lakes or in specific  
50 regions including North America (Clague and Evans 2000; O’Connor et al., 2001; McKillop and Clague,  
51 2007a,b), South America (Emmer and Vilímek, 2013; Anaconda et al., 2015; Cook et al., 2016; Emmer  
52 et al., 2016a; Frey et al., 2016), the European Alps (Huggel et al., 2004; Frey et al., 2010), central Asia  
53 (Bolch et al., 2008; Mergili and Schneider, 2011; Petrov et al., 2017), and the Himalayas (Wang et al.,  
54 2008; Ives et al., 2010; ICIMOD, 2011; Ashraf et al., 2012; Worni et al., 2013; Watson et al., 2015;  
55 Aggarwal et al., 2016; Rounce et al., 2016).

56 Existing GLOF hazard and risk assessments are usually designed for specific purposes (e.g. estimating  
57 hazard, susceptibility or risk), specific regions or sites, specific lake contexts (e.g. ice-dammed or  
58 moraine-dammed), or require certain types, amounts, or detail of input data, or some combination of  
59 the above. These tailored risk assessments are very valuable for their stated purpose, but because of  
60 their specific conditions, the extent to which these techniques can be applied to other areas or lake  
61 types is uncertain, which itself often necessitates the development of additional region-, site-, or  
62 context-specific risk or hazard assessments. In addition, there is often a lack of transparency about  
63 why specific criteria are chosen, indicating that hazard and risk assessments are sometimes subjective  
64 in their design (McKillop and Clague, 2007a, b).

65 Nonetheless, some hazard and risk assessments, although developed initially for, and applied to,  
66 specific regions, have been designed in such a way that they can be applied elsewhere. Most are

67 designed for moraine-dammed lakes. Notable examples include those of McKillop and Clague (2007b),  
68 Mergili and Schneider (2011), and Rounce et al. (2016). McKillop and Clague (2007b) developed an  
69 objective method for assessing outburst flood hazard from moraine-dammed lakes in British  
70 Columbia, which uses remote sensing methods. Nevertheless, as a hazard assessment it does not  
71 evaluate impacts, exposure, vulnerability or risk, and cannot be applied to bedrock- or ice-dammed  
72 lakes, which may also exist within the same region. Mergili and Schneider (2011) developed a GLOF  
73 hazard assessment based on remote sensing data that could be applied to any lake type, but their  
74 method does not consider impacts on humans or infrastructure. Rounce et al. (2016) presented an  
75 objective and repeatable method for GLOF hazard and impact assessment, but this was based on  
76 moraine-dammed lakes only.

77 The purpose of this study is to present a decision-aid procedure that can be employed to identify those  
78 lakes within any given region that represent the greatest GLOF threat to downstream communities  
79 and infrastructure. This procedure, which employs Multi-Criteria Decision Analysis (MCDA), is not  
80 specific to any one glacial lake type, which is desirable because it permits the relative threat of impact  
81 to be assessed simultaneously for moraine-, ice-, and bedrock-dammed lakes, all of which may exist  
82 within the region of interest, as well as composite forms. This enables the generation of standardised  
83 results and the determination of appropriate action across the spectrum of glacial lake types. As with  
84 some existing GLOF hazard and risk assessments, our MCDA method also uses freely and widely  
85 available data and software, without the need for detailed site knowledge, nor field-derived data. As  
86 we explain in Section 2, MCDA involves the application of strict rules about the use of exhaustive, non-  
87 redundant and consistent criteria through the formulation of a 'Description Problem', meaning that  
88 subjective selection of criteria is minimised. Another key advantage of the software used for MCDA is  
89 that sensitivity analyses are readily undertaken such that the robustness of the model and its  
90 assumptions can be evaluated. To our knowledge, sensitivity analysis has not been undertaken for any  
91 previous GLOF hazard or risk assessment. We envisage that our method is most appropriately applied  
92 to regions where a variety of glacial lake types exist so that their relative threat can be assessed  
93 simultaneously, where field data are sparse or non-existent, and as a preliminary assessment of the  
94 threat posed by GLOFs to people or infrastructure. Once the most dangerous lakes are identified,  
95 future detailed field campaigns, flood modelling, and risk mitigation strategies can be employed. An  
96 example of where such an approach would be of value is the Bolivian Andes (Cook et al., 2016) where  
97 GLOFs from a range of glacier lake types pose a possible threat to downstream areas, but field data  
98 are sparse, and collection of such data would be complicated by poor accessibility to sites.

99 Our objectives are: (1) to define a set of robust (i.e. exhaustive, non-redundant, consistent)  
100 susceptibility and potential downstream impact criteria that will be used to define GLOF risk; (2) to

101 use these criteria to assess GLOF risk for 22 lakes around the world and compare our results with those  
102 of previous GLOF risk and hazard studies; (3) to undertake sensitivity testing of the MCDA model in  
103 order to evaluate the robustness of the method; and (4) apply our model to assess the risk posed by  
104 25 lakes in the Bolivian Andes, which represents a case study of how our model could be used.

105 A range of terms have been used interchangeably and inconsistently in GLOF 'hazard' and 'risk'  
106 studies. These include 'hazard', 'risk', 'susceptibility', 'danger', 'threat', 'impact', 'exposure', and  
107 'vulnerability'. Further, definitions of 'hazard' and 'risk' can vary significantly between different  
108 branches of risk management science. In the natural sciences, for example, 'risk' is often taken to be  
109 the product of hazard and vulnerability, and sometimes exposure also (e.g. IPCC, 2014); however,  
110 international guidelines for the broad and varied fields of risk management science do not necessarily  
111 subscribe to such algorithms (see ISO 31000:2009 and The Society for Risk Analysis glossary). For the  
112 purposes of our MCDA model, we consider the physical properties of the glacial lakes, and the  
113 characteristics of the surrounding landscape and environmental context that may promote or trigger  
114 a GLOF event, to be the 'susceptibility' factors that drive the 'hazard' (i.e. a GLOF). The criteria  
115 associated with effects on downstream communities in our MCDA model are termed 'potential  
116 downstream impacts'. Whilst the product of susceptibility and downstream impacts do not equal risk  
117 according to the aforementioned algorithm sometimes used in natural risk science, we use the term  
118 'risk' here to refer to consideration for, and combination of, impacts and susceptibility. This is a  
119 convenient short-hand term, and remains consistent with the more general definitions of risk laid out  
120 in ISO 31000:2009.

## 121 **2. Methodology**

### 122 **2.1 Background to setting an MCDA problem**

123 MCDA is a sub-field of operations research and management science that focuses on the development  
124 of decision support tools and methodologies to resolve complex decision problems. It has been  
125 applied previously across a number of environmental and natural disaster related problems including  
126 floods, landslides, avalanches and water management (e.g. Merad et al., 2004; Marinoni, 2005; Lin,  
127 2008; Akgun 2010; Behzadian et al., 2010; Huang et al., 2011; Stecchi et al., 2012; Tacnet et al., 2014;  
128 Brito and Evers, 2016). It is notable that MCDA has not yet been applied to assess GLOF risk.  
129 Specifically, MCDA can be applied across a region that contains numerous glacial lake types in order  
130 to determine which lakes, if any, should be selected for more detailed analysis, monitoring, or  
131 remediation work. The use of freely available tools and datasets, and the ease and relatively rapid  
132 deployment of our MCDA approach makes this an effective and efficient technique in areas where  
133 detailed knowledge and field data are limited.

134 In MCDA, a typical problem would be the task of defining the risk between a finite set of decision  
135 alternatives (e.g. determining, from a population of glacial lakes, which lakes could generate  
136 dangerous GLOFs), each of which is characterised by a set of criteria that must be considered  
137 simultaneously (Ishizaka et al., 2012). In this case, we consider all alternatives (i.e. glacial lakes) in a  
138 region that are characterised by a set of criteria (e.g. regional seismic activity, dam stability, potential  
139 loss of life, etc.). In practice, problems faced by experts or decision-makers in natural hazard or risk  
140 management can be a combination of four basic problems (Roy, 1996):

141 a) **Description Problem:** This is used in order to provide a number of alternatives (e.g. dangerous  
142 glacial lakes) and a suitable set of criteria, without making any recommendation about the  
143 final decision (e.g. which lakes represent the highest risk). Criteria that will be used in the  
144 MCDA are chosen according to past literature and a set of guidelines that will be discussed in  
145 section 2.2.

146 b) **Sorting Problem:** Alternatives (i.e. glacial lakes) are sorted into ordered, pre-defined  
147 categories. A sorting problem can also be used for screening in order to reduce the number  
148 of alternatives that are to be considered. For example, all lakes within the study area are  
149 sorted according to GLOF risk for downstream communities with categories such as “high  
150 risk”, “medium risk”, and “low risk”.

151 c) **Ranking Problem:** Alternatives (i.e. glacial lakes) are classified from highest to lowest risk;  
152 equal ranks are possible. For example, all lakes in the study area are ascribed a numerical  
153 value from 1 to  $n$  depending on their level of GLOF risk to downstream communities, but some  
154 lakes may have risk equal to one another and so share the same rank value.

155 d) **Choice Problem:** This is used to select a single alternative or to reduce the group of  
156 alternatives to a subset of equivalent or incomparable alternatives. An example would be to  
157 select a single lake with the highest risk to downstream population; all other lakes would be  
158 excluded from further analysis.

159 Previous studies of GLOF hazard or risk have used a wide range of criteria, which reflects variability in  
160 the type and amount of data available, and the specific objectives of the assessment procedure (e.g.  
161 evaluating hazard or risk, across a region or individual site, and for different lake contexts). Hence, the  
162 first task of this study can be framed as a Description Problem, where the main (sub-) criteria that  
163 determine the risk of a lake outburst to downstream communities must be defined, with consideration  
164 for the range of assessment criteria used in previous studies.

165 Next, these criteria will be used to frame a Sorting Problem whereby lakes will be classed according  
166 to high, medium or low risk, which can be used to narrow future research or mitigation focus onto the

167 most dangerous lakes. The Sorting Problem has been chosen in this study instead of ranking or choice  
168 problems because it offers the possibility of evaluating a large set of lakes, but also a single lake. The  
169 Ranking Problem suffers from the shortcoming that at least two lakes need to be studied in order for  
170 the assessment to take place; the Choice Problem will only define the highest risk lake. Our MCDA  
171 approach for GLOF risk is designed to be intuitive, to use freely available datasets, and be applicable  
172 to any glacial lake irrespective of dam type or region of the world.

## 173 **2.2 The description problem: determining the criteria that define GLOF risk**

174 Previous reviews of GLOF hazard and risk assessments have highlighted how a wide variety of criteria  
175 have been used in different studies to determine GLOF risk (e.g. Emmer and Vilímek, 2013; Rounce et  
176 al., 2016). Others have gone further, suggesting that many assessments are made through subjective  
177 and non-transparent selection of criteria (McKillop and Clague, 2007b). MCDA alleviates this issue to  
178 some extent by developing a “coherent set” of criteria. In order to achieve this, the following  
179 properties need to be fulfilled (Roy, 1996):

- 180 • **Exhaustiveness:** all possible criteria are taken into account, and nothing important is left out.  
181 For example, a criterion, such as rockfall/landslide susceptibility, is actually a composite of  
182 multiple criteria (e.g. slope steepness, seismic activity, etc.) (Fig. 1). Hence, such composite  
183 criteria should be split into separate criteria to avoid bias in the final estimation of risk. This  
184 has not always been done in previous studies (e.g. Costa and Schuster, 1988; Huggel et al.,  
185 2004; Bolch et al., 2008; Emmer and Vilimek, 2013; Aggarwal et al., 2016; Rounce et al., 2016).  
186 Table 1 shows the exhaustive list of 79 criteria from which 13 have been selected.
- 187 • **Non-redundancy:** no double counting; all the unnecessary criteria must be removed. Some  
188 assessments effectively examine the same criteria twice, which biases the risk assessment.  
189 For example, glacier snout steepness and presence of a crevassed glacier snout above the lake  
190 both lead to a greater probability of ice calving into the lake, which raises the risk of a GLOF  
191 (e.g. Grabs and Hanisch, 1993; Zapata, 2000; Wang et al., 2011). However, these two criteria  
192 are strongly related - steeper glaciers will generally flow faster, which causes more crevassing,  
193 and greater ice calving potential. Therefore, only one representative criterion should be  
194 evaluated.
- 195 • **Consistency:** the criteria must not hide any preferences. A criterion can only have a positive  
196 or negative effect on the choice of alternative (e.g. lake), but can never have both effects  
197 simultaneously. For example, glacier shrinkage can have a two-way effect. For moraine-  
198 dammed lakes, glacier shrinkage will reduce the risk of calving or ice/snow avalanches into  
199 the lake, and hence reduce the risk of a GLOF produced by a displacement wave. But, for ice-  
200 dammed lakes, glacier shrinkage can increase the risk of GLOFs because the ice dam

201 disintegrates or becomes more susceptible to flotation or tunnelling by meltwater (e.g. Tweed  
202 and Russell, 1999). Hence, criteria need to be selected such that their effects operate in the  
203 same direction. This rule has not been used yet in previous assessments since these studies  
204 do not usually perform an evaluation across multiple dam types. Nevertheless, this is  
205 important in our study as the MCDA method we are using is applicable across all dam types.

206 In an attempt to meet these characteristics, we compiled a list of all the criteria that have  
207 previously been used in GLOF risk and hazard assessments (Table 1). Several studies (e.g. Huggel  
208 et al., 2004; Bolch et al., 2008; Mergili and Schneider, 2011; Emmer and Vilímek, 2013; Worni et  
209 al., 2013; Rounce et al., 2016) have also compiled and/or reviewed a number of these criteria.  
210 However, in many studies, the final selection of criteria that are used to make the risk assessment  
211 is often made (1) seemingly on a subjective or non-transparent basis, or (2) based on the  
212 frequency of use in previous studies (e.g. a tally chart). To some extent, this reflects specific local  
213 or regional needs or issues, or specific data requirements or availability. But for areas where there  
214 are limited data or knowledge, the MCDA guidelines outlined above serve to reduce user bias in  
215 the selection of criteria by first considering all available criteria, and streamlining them to avoid  
216 issues of non-exhaustiveness, redundancy, and non-consistency. Table 1 was generated from 30  
217 studies and lists 79 factors in total. Through consideration of their exhaustiveness, non-  
218 redundancy, and consistency, we identified 13 criteria that can be used for GLOF risk analysis of  
219 any lake, in any part of the world, from freely available data or satellite imagery. Hence, several  
220 criteria were rejected because they were either non-exhaustive, redundant, or non-consistent,  
221 would have necessitated fieldwork, or that were specific to a region or a particular lake type. Fig.  
222 1 illustrates how, from the 13 criteria, lakes are assessed according to their GLOF risk. Details  
223 about each criterion are provided in the Supplementary Data - Appendix A. If local data exist for  
224 any of these criteria, their use is strongly encouraged.

225

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228

229 Fig. 1. Flow diagram of the GLOF risk assessment procedure. Supplementary information about the final set of criteria can be found in Appendix A.

230  
231  
232

**Table 1 - Review of criteria assessed in previous studies. Top section outlines the process followed to accept or reject a criterion. Middle section shows the results. Bottom section illustrates the literature used. The accepted criteria in the middle section are illustrated in Fig. 1.**

accepted/rejected criterion	reason	indication
rejected criterion	dam, region or scenario specific	A
	field assessment required	B
	non-exhaustive	C
	redundant	D (with which criterion)
	non-consistent	E
accepted criterion	no issue	✓

ID	criterion	source	accepted/rejected criterion
TR.1	regional seismic activity	4,15,18,28	✓
TR.2	precipitation seasonality (intense precipitation events)	8,13	✓
TR.3	temperature seasonality (high temperature events)	8,13	✓
ME.1	dam freeboard	2,3,4,5,15,17,18,21,30	✓
ME.2	dam type	4,8,12,15,17,29,30	✓
ME.3	steepest slope surrounding lake	6,11,14	✓
ME.4	distance between lake and steepest slope	9,26	✓
ME.5	distance between lake and glacier	2,4,5,14,16,24,26	✓
ME.6	parent glacier snout steepness	2,4,11,13,16	✓
SR.1	travel distance of GLOF	8,17,23,28	✓
SR.2	lake volume	4,7,21,26	✓
IM.1	potential loss of human life	28	✓
IM.2	potential loss of infrastructure	28	✓
1	hydrometeorological situation	18	C
2	mass movement into lake/potential for lake impact	1,8,11,18,21,24,30	C
3	snow avalanche/icefall susceptibility	4,7,14,15,17,21,28	C
4	rockfall/landslide susceptibility	2,3,4,14,15,17,21,28	C
5	slope of lateral moraines and possibility of its fall into the lake	2,19	C
6	interconnected lakes/unstable lake upstream	6,18,24,28,30	C
7	calving susceptibility	15	C
8	slope between lake and glacier snout	16	D (with ME.6)
9	crevassed glacier snout above lake	2,3,4	D (with ME.6)
10	stagnant ice at the glacier terminus	14	B
11	area of the mother glacier	13,16	E
12	glacier advance	2	E
13	glacier shrinkage	14	E
14	reaction of the glacier to climate change	11	E
15	contact with glacier	6,26	D (with ME.5)
16	maximum area of inundation	10	D (with SR.1)
17	amount of loose material/maximum debris flow volume	6	B

18	lake area and/or size	4,10,14,19,24,26	D (with SR.2)
19	breach volume	6	B
20	lake area change	11,14,15,28	D (with SR.2)
21	lake depth	4,21,26	D (with SR.2)
22	distant flank steepness of the dam	1,4,13,15,16	A,B
23	width and/or height ratio of dam	3,4,8,10,12,13	B
24	top width of dam	13,19	A, B
25	steepness of moraine	2	A
26	pipng/seepage through moraine	2,3,4,7,12,15,19	A,B
27	buried ice in moraine	1,2,7,8,10,11,13	A,B
28	main rock type of moraine	10	A,B
29	moraine slope stabilised by vegetation	1	A
30	supra/englacial drainage	7,30	A,B
31	pipng gradient	19	A,B
32	lake perimeter	19	A
33	lake width	19	A
34	dam height	19	A
35	maximum slope of distal face of the dam	19	A,B
36	mean slope between lake and glacier	19	D (with ME.6)
37	mean slope of lake surrounding	19	D (with ME.3)
38	hydrostatic pressure	28	B
39	lake elevation	20	D (with TR.2)
40	nonglacial watershed component	20	D (with TR.2)
41	mean stream size	20	D (with TR.2)
42	drainage density	20	D (with TR.2)
43	mean slope	20	D (with TR.2)
44	population density	22	B
45	livestock density	22	B
46	cultivated area	22	B
47	density of road network	22	B
48	density of agricultural economy	22	B
49	proportion of rural population	22	B
50	percentage of small livestock	22	B
51	road level	22	B
52	building level	22	B
53	regional GDP	22	B
54	financial revenue share of GDP	22	B
55	density of fixed assets investment	22	B
56	female population	25	B
57	population < 6 years of age	25	B
58	population > 60 years of age	25	B
59	literacy rate	25	B
60	unemployment	25	B
61	employment in farming	25	B

62	disabled population	25	B
63	home renters	25	B
64	derelict houses	25	B
65	water availability	25	B
66	medical facilities	25	B
67	education facilities	25	B
68	banking services	25	B
69	access to radio	25	B
70	access to TV	25	B
71	access to internet	25	B
72	access to mobile	25	B
73	access to vehicle	25	B
74	economical vulnerability	27	B
75	social vulnerability	27	B
76	institutional vulnerability	27	B
77	building materials	27	B
78	geology and type of soil	27	B
79	land use laws	27	B

1: Costa and Schuster (1988); 2: Grabs and Hanisch (1993); 3: Clague and Evans (2000); 4: Zapata (2000); 5: O'Connor et al. (2001); 6: Huggel et al. (2002); 7: Reynolds (2003); 8: Huggel et al. (2004); 9: Rickenmann (1999, 2005); 10: McKillop and Clague (2007a, b); 11: Bolch et al. (2008); 12: Hegglin and Huggel (2008); 13: Wang et al. (2008); 14: Bolch et al. (2011); 15: Mergili and Schneider (2011); 16: Wang et al. (2011); 17: Worni et al. (2013); 18: Emmer and Vilímek (2013); 19: Emmer and Vilímek (2014); 20: Allen et al. (2015); 21: Vilímek et al. (2015); 22: Wang et al. (2015); 23: Watson et al. (2015); 24: Allen et al. (2016); 25: Aggarwal et al. (2016); 26: Cook et al. (2016); 27: Frey et al. (2016); 28: Rounce et al. (2016); 29: Carrivick and Tweed (2016); 30: Petrov et al. (2017).

233

234 **2.3 The sorting problem: Past GLOF events and potentially dangerous lakes**

235 Following the identification of appropriate selection criteria from the Description Problem stage, all  
236 lakes within a region can be judged according to those criteria in order to determine which lakes, if  
237 any, represent a GLOF risk to downstream communities. This can be achieved remotely (i.e. without  
238 the need for fieldwork), and without cost, as we demonstrate below. Our approach can be applied to  
239 a single lake or to a complete lake inventory within a region. It would be particularly useful in  
240 identifying sites for further detailed field studies, outburst flood modelling, or monitoring. In this  
241 study, we apply our method on a number of lakes that had been identified in previous studies as  
242 representing a threat to downstream communities. Fig. 2 illustrates the steps that need to be followed  
243 for the method to be applied in a chosen region. For the trigger criteria (TR.1, 2, 3), the user will need  
244 to open the indicated databases (Global seismic hazard map, BIOCLIM variables 4 and 5) in a GIS in  
245 order to evaluate the lakes. For all other criteria, Google Earth Pro is sufficient for evaluation.  
246 Additional information about criteria evaluation can be found in Table 2 and Appendix A.

### STEP 1: Download the data and software

- a) Most recent Landsat/Sentinel 2 images of the area of interest
- b) Global seismic hazard map (<http://gmo.gfz-potsdam.de/index.html>)
- c) BIOCLIM variables BIO 4 & BIO 15 (<http://www.worldclim.org/bioclim>)
- d) Google Earth Pro
- e) SMAA-TRI software (<http://smaa.fi/jsmaa/>)



### STEP 2: Determine potentially dangerous lakes

- a) Use Normalized Difference Water Index to select lakes (Bolch et al., 2011)
- b) Remove lakes with area <math><0.01\text{km}^2</math> (Worni et al., 2013)
- c) Remove lakes with distance >500m from glaciers (Wang et al., 2011)
- d) Remove lakes with distance >500m from a >25° slope OR <500m from a <25° slope (Wang et al., 2011; Wang et al., 2015; Alean, 1985; Zemp, 2002)
- d) Remove lakes that do not contain infrastructure at a higher than 3° average slope between lake and end-point of a possible outburst (Huggel et al., 2004)



### STEP 3: Assess GLOF risk

- a) Introduce the following to the SMAA-TRI software:
  - list of lakes (see step 2)
  - the 13 evaluation criteria shown in Figure 1
  - the 3 risk categories (low/medium/high)
- b) Assign a risk level for each criterion and lake (1=low; 2=medium; 3=high).
- c) Run analysis



### STEP 4: Sensitivity analysis

- a) Lambda cutting level sensitivity analysis
- b) Criteria thresholds sensitivity analysis

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248 **Fig. 2. Five-step flow diagram for the Multi-Criteria Decision Analysis (MCDA) method. Step 1: the user downloads all data**  
249 **and software needed for the evaluation; Step 2: the proglacial lake dataset to be analysed is extracted; Step 3: introducing**  
250 **the parameters to the software and computation of the result; Step 4: Sensitivity Analysis**

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#### 252 **2.3.1 Choice of lakes for testing**

253 Our MCDA method was applied to 22 glacial lakes from a number of locations around the world in  
254 order to test and evaluate the performance of the model globally. We chose a mix of lakes that have  
255 been the subject of previous GLOF hazard or risk studies (where MCDA has not been used), as well as  
256 lakes that are known to have generated GLOFs. The 6 GLOF-generating lakes were selected based on  
257 two important characteristics:

- 258 • There is existing literature describing the downstream impact of the GLOF;
- 259 • There is free, high-resolution satellite imagery (e.g. integrated into Google Earth) before the  
260 GLOF event, which makes the pre-GLOF lake risk assessment possible.

261 Of these lakes, one is located in Norway (Flatbreen lake - Breien et al., 2008), one in Bolivia (Keara -  
262 Hoffmann and Wegenmann, 2013), one in Peru (Lake 513 - Carey et al., 2012; Klimeš et al., 2014;  
263 Vilímek et al., 2015), one in Nepal (Halji lake - Kropáček et al., 2015;), one in Pakistan (Passu lake -  
264 Ashraf et al., 2012), and one in India (Chorabari lake - Das et al., 2015). Hence, a wide range of locations  
265 are represented.

266 The remaining 16 lakes have not yet burst but are considered potentially dangerous by other GLOF  
267 hazard/risk assessments that have made use of multiple criteria: one is located in Peru (Hanpi k'ocha  
268 - Frey et al., 2016), five are located in India (Gopang Gath, Spong Tongpo, Schako Tsho - Worni et al.,  
269 2013; Chollamo, Lake 0071 - Aggarwal et al., 2017), eight in Nepal (Imja Tsho, Tsho Rolpa, Thulagi  
270 Tsho, Dig Tsho, Lower Barung Tsho, Ludming Tsho, Chamlang South Tsho, Chamlang North Tsho -  
271 Rounce et al., 2016) and two in New Zealand (Maud lake, Godley lake - Allen et al., 2009). Values for  
272 each criterion were assigned for the lakes (see also Supplementary Data - Appendix B, Tables B.1 and  
273 B.2) and the analysis was run using the SMAA-TRI software (see section 2.3.2).

### 274 **2.3.2 SMAA-TRI software**

275 A range of different software packages and methods have been developed for resolving complex  
276 sorting problems in MCDA: e.g. FlowSort (Nemery and Lamboray 2008), ELECTRE-Tri (Mousseau et al.,  
277 2000), AHPSort (Ishizaka et al., 2012). ELECTRE-TRI has been used by Merad et al. (2004) to identify  
278 zones subject to mining-induced risk; Stecchi et al. (2012) used the same software to assess  
279 vulnerability due to ground deformation phenomena. In this study, we use SMAA-TRI (Stochastic  
280 Multi-criteria Acceptability Analysis, <http://smaa.fi/>), a free-to-download upgraded version of  
281 ELECTRE-TRI (Tervonen et al., 2012). SMAA methods allow the tackling of problems with imprecise  
282 information, similar to the criteria used in GLOF multi-criteria assessments. Imprecise information  
283 means that the value is present but not always with the required precision (Tervonen et al., 2012;  
284 Malczewski and Rinner, 2015). A review of all the ELECTRE method packages can be found in Figueira  
285 et al. (2013).

### 286 **2.3.3 Setting risk thresholds and codes for evaluating individual criteria**

287 Table 2 presents the threshold values that we have used to define the risk classes for each criterion in  
288 the sorting method (see also Supplementary Data - Appendix A). The software allows the user to set  
289 the evaluation codes. For this model, three codes were set: 1 (low risk), 2 (medium risk) and 3 (high  
290 risk). These values are used to assign each criterion to a predefined risk class, from which a total risk  
291 score can be calculated for each lake.

292 The relative importance of each criterion can differ, and there are numerous methods for determining  
293 the relative weights of individual criteria (Saaty, 1977; Chen et al., 2001; Figueira and Roy, 2002). In a

294 natural hazard context, weights are typically determined subjectively by the hazard/risk experts or  
295 based on statistical methods (such as regression and principal component analysis) (Chen et al., 2001).  
296 However, since there is insufficient empirical evidence by which to determine the relative importance  
297 of each criterion in GLOF risk or hazard assessments, the decision was made here not to assign any  
298 weights. Nonetheless, this could be undertaken in future studies if understanding of GLOF controlling  
299 factors were to develop sufficiently.

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311 **Table 2 – Criteria units, evaluation methods, main risk thresholds and sensitivity analysis thresholds. Details on criteria threshold determination can be found in Appendix A.**

ID	Criteria	Unit	Low risk	Medium risk	High risk	Evaluation tool	Sensitivity analysis	Threshold variations for sensitivity analysis
<b>Triggers</b>								
TR.1	regional seismic activity	pga in $m/s^2$	<0.5	0.5-3.9	>3.9	USGS/Global Seismic Hazard Map-GSHAP	✓	<0.5, 0.5-1.9, >1.9
TR.2	intense precipitation events	precipitation seasonality in %	<50	50-100	>100	Bioclim 15 - precipitation seasonality	✓	<25, 25-75, >75
TR.3	high temperature events	temperature seasonality in %	<50	50-100	>100	Bioclim 4 - temperature seasonality	✓	<25, 25-75, >75
<b>Mechanisms</b>								
ME.1	dam freeboard	m	>15	15-5	<5	Google Earth/Bing Maps		not enough detail
ME.2	dam type	type	bedrock	moraine	ice	Google Earth/Bing Maps		qualitative
ME.3	steepest slope surrounding lake	degrees	<30	30-45	>45	Google Earth/Bing Maps	✓	<20, 20-30, >30
ME.4	distance between lake and steepest slope	m	500-250	250-10	10-contact	Google Earth/Bing Maps	✓	500-250, 250-50, <50
ME.5	distance between lake and glacier	m	500-250	250-10	10-contact	Google Earth/Bing Maps	✓	500-250, 250-50, <50
ME.6	parent glacier snout steepness	degrees	<15	15-25	>25	Google Earth/Bing Maps		not enough detail
<b>Flood wave size/runout</b>								
SR.1	travel distance of GLOF	degrees	3-7	7-11	>11	Google Earth/Bing Maps	✓	3-6, 6-9, >9
SR.2	lake volume	$m^3 * 10^6$	$<1 * 10^6$	$1 * 10^6 - 10 * 10^6$	$>10 * 10^6$	Google Earth/Bing Maps for area + equation	✓	$<0.1 * 10^6, 0.1 * 10^6 - 1 * 10^6, >1 * 10^6$ (1 order of magnitude lower threshold)
<b>Impact</b>								
IM.1	potential loss of human life	individuals	<10	10-1000	>1000	Google Earth/Bing Maps/web info	✓	<10, 10-100, >100
IM.2	potential loss of infrastructure	infrastructure	agricultural fields, roads etc.	houses, bridges etc.	hydropower, mining camp etc.	Google Earth/Bing Maps/web info		qualitative

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#### 317 **2.3.4 Sensitivity analysis**

318 In MCDA, sensitivity analysis serves to determine how much the uncertainty of the results of a model  
319 are influenced by the uncertainty of its input criteria (Saltelli et al., 1999). Sensitivity analysis can be  
320 performed using different methods. The robustness of the model can be assessed by analysing its  
321 sensitivity to the alteration of parameter  $\lambda$  (lambda), the criteria thresholds, and their assigned  
322 weights (Roy, 1993). The criteria used in this study do not hold weights, so the two sensitivity analyses  
323 to be undertaken are (1) the alteration of the  $\lambda$ -cutting level, and (2) the variation of the criteria  
324 thresholds.

##### 325 **2.3.4.1 Lambda cutting level**

326 The  $\lambda$ -cutting level indicates how many of the criteria have to be fulfilled in order to assign an  
327 alternative (i.e. a lake) to a specific risk category, and it can be altered within the software. The cutting  
328 level must be set to between 0.5 and 1.0 (Damart et al., 2007); a cutting level of 0.5 means that at  
329 least 50% (i.e. 7 criteria) of the 13 criteria would need to be evaluated as 'high risk' in order to assign  
330 a lake in the high risk category overall. Several studies have discussed the assignment of an  
331 appropriate cutting level, and it is generally accepted that it should be greater than the highest weight  
332 (Figueira and Roy, 2002; Merad et al., 2004; Brito et al., 2010; Tervonen et al., 2012; Sánchez-Lozano,  
333 2014). Since no weights were assigned in this study, we present a series of scenarios in Table 4 where  
334 the cutting level is set to 0.65, 0.7, 0.75, 0.8, and 0.85. The objective here is to assess whether any  
335 lakes change risk category as the cutting level is changed from its least conservative level (0.65) to its  
336 most conservative level (0.85). The percentages in each risk class show the level of confidence with  
337 which the software assigns each lake to a class. The higher the percentage, the higher the probability  
338 of a lake belonging to that specific risk class. If percentages between two risk classes are equal, then  
339 the GLOF risk for that lake will be classified automatically in the higher risk class, since risk analysis is  
340 generally a conservative exercise (Merad et al., 2004).

##### 341 **2.3.4.2 Criteria thresholds**

342 The second sensitivity analysis examines the extent to which risk classifications will change if the  
343 threshold values used for each criterion are altered (both the original thresholds and the revised  
344 thresholds used for the sensitivity analysis can be found in Table 2). For this analysis, the  $\lambda$ -cutting  
345 level was kept at 0.65, and thresholds were changed for 9 of the 13 criteria; thresholds for the 4  
346 remaining criteria (ME.1, 2, 6 and IM.2) could not be altered either because the resolution of the  
347 remote sensing data was insufficient to allow any meaningful threshold changes to be made, or  
348 because of the qualitative nature of the threshold limits. We took a conservative approach whereby  
349 the thresholds for the highest levels of risk for each criterion were relaxed in order to determine  
350 whether any lakes then fell into the high risk category overall.

351 **3. Results**

352 **3.1 Assessing GLOF risk: an application to past and potential future events**

353 Table 3 shows the lakes considered in this study alongside the level of risk posed to downstream  
 354 communities, which was determined using our MCDA approach. The results show that 11 lakes pose  
 355 a high risk to downstream communities, six lakes are ranked as medium risk, and five as low-risk. Since  
 356 susceptibility and downstream impacts are both evaluated in the same computational step, the  
 357 outcome (risk classes) shows the combination of GLOF impact severity and potential outburst  
 358 susceptibility. A lake can become classified as high risk either due to high outburst susceptibility  
 359 parameters, such as elevated regional seismic activity and steep slopes surrounding the lake, or  
 360 because of severe potential impacts, such as a large population downstream, or the presence of high-  
 361 value infrastructure.

362 **Table 3 – Potentially dangerous lakes and selected GLOF events derived from previous studies. Risk level derived from the**  
 363 **MCDA method. Decimal percentages (i.e. from 0.5 to 1) indicate the level of confidence that a lake belongs to the specific**  
 364 **risk class. Low risk = Green, Medium risk = Orange, High risk = Red.**

Dangerous lakes - literature	Country	Reference	Coordinates in UTM			Risk Level
Maud Lake	New Zealand	Allen et al., 2009	59 G	459482	5185818	0.97
Godley Lake	New Zealand	Allen et al., 2009	59 G	461555	5188206	0.89
Chholamo	India	Aggarwal et al., 2017	45 R	672675	3099360	0.89
Lake 0071	India	Aggarwal et al., 2017	45 R	676212	3084379	0.58
Hanpi k'ocha	Peru	Frey et al., 2016	18 L	743739	8534059	0.62
Gopang Gath	India	Worni et al., 2013	43 S	708269	3601049	0.92
Spong Tongpo	India	Worni et al., 2013	43 S	658545	3769166	0.70
Schako Tsho	India	Worni et al., 2013	45 R	658915	3095511	0.78
Imja Tsho	Nepal	Rounce et al., 2016	45 R	492610	3085944	0.78
Tsho Rolpa	Nepal	Rounce et al., 2016	45 R	448360	3082066	0.97
Thulagi Tsho	Nepal	Rounce et al., 2016	45 R	253755	3153985	1.00
Dig Tsho	Nepal	Rounce et al., 2016	45 R	459210	3083375	0.99
Lower Barung Tsho	Nepal	Rounce et al., 2016	45 R	509355	3074824	0.97
Ludming Tsho	Nepal	Rounce et al., 2016	45 R	461884	3072885	0.92
Chamlang South Tsho	Nepal	Rounce et al., 2016	45 R	495956	3069986	0.91
Chamlang North Tsho	Nepal	Rounce et al., 2016	45 R	495685	3073227	0.91
Selected GLOF events	Country	Reference	Coordinates in UTM			Risk Level
Flatbreen lake - 2004	Norway	Breien et al., 2008	32 V	382775	6817696	0.57
Passu lake - 2007	Pakistan	Ashraf et al., 2012	43 S	489281	4034749	0.65
Keara lake - 2009	Bolivia	Hoffmann and Wegenmann, 2013	19 L	481958	8377253	0.52
513 lake - 2010	Peru	Carey et al., 2012; Klimeš et al., 2014; Vilimek et al., 2015	18 L	219809	8980678	0.65
Halji lake - 2011	Nepal	Kropáček et al., 2015	44 R	545635	3348799	0.79
Chorabari lake - 2013	India	Das et al., 2015	44 R	314434	3403219	0.59

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366 **3.2 Lambda cutting level sensitivity analysis**

367 The results of this first sensitivity analysis are shown in Table 4. All lakes that are already classified as  
 368 high risk when the cutting level is at 0.65 will not change class with an increase in the cutting level.  
 369 This is because as the cutting level is increased (0.70, 0.75, etc.), a lower proportion of criteria graded  
 370 as 'high risk' (30%, 25%, etc.) are needed in order to classify a lake as 'high risk' overall. Lakes classified  
 371 as medium or low-risk when the cutting level is 0.65 may be reclassified into a higher risk class as the  
 372 cutting level is increased. Taking the example of the five low-risk lakes, the number of low-risk criteria  
 373 is sufficiently important to maintain the lakes as low risk no matter what cutting level is used. Two of

374 the lakes classed as medium risk with a cutting level of 0.65 (Keara Lake and Hanpi k'ocha) move into  
 375 high-risk categories when the cutting level is increased by one increment to 0.7, and a further three  
 376 when the cutting level is increased to 0.75. Gopang Gath is the only lake that maintains its medium-  
 377 risk score until the penultimate computational step ( $\lambda = 0.80$ ), after which it shifts to high risk ( $\lambda =$   
 378 0.85).

379 **Table 4 - Sensitivity analysis based on alteration of the lambda cutting level. Decimal percentages (i.e. from 0.5 to 1)**  
 380 **indicate the level of confidence that a lake belongs to the specific risk class. Low risk = Green, Medium risk = Orange, High**  
 381 **risk = Red.**

Dangerous lakes - literature	$\lambda$ -cutting level				
	0.65	0.7	0.75	0.8	0.85
Maud Lake	0.97	0.98	0.97	0.93	0.86
Godley Lake	0.89	0.89	0.84	0.72	0.56
Chholamo	0.89	0.89	0.84	0.73	0.56
Lake 0071	0.58	0.72	0.82	0.87	0.84
Hanpi k'ocha	0.62	0.49	0.64	0.79	0.91
Gopang Gath	0.92	0.83	0.70	0.50	0.44
Spong Tongpo	0.70	0.53	0.38	0.56	0.73
Schako Tsho	0.78	0.88	0.94	0.98	1.00
Imja Tsho	0.78	0.88	0.95	0.98	1.00
Tsho Rolpa	0.97	0.99	1.00	1.00	1.00
Thulagi Tsho	1.00	1.00	1.00	1.00	1.00
Dig Tsho	0.99	1.00	1.00	1.00	1.00
Lower Barung Tsho	0.97	0.99	1.00	1.00	1.00
Ludming Tsho	0.92	0.96	0.99	1.00	1.00
Chamlang South Tsho	0.91	0.96	0.99	1.00	1.00
Chamlang North Tsho	0.91	0.96	0.99	1.00	1.00
Selected GLOF events	$\lambda$ -cutting level				
	0.65	0.7	0.75	0.8	0.85
Flatbreen Lake - 2004	0.57	0.68	0.73	0.69	0.55
Passu Lake - 2007	0.65	0.49	0.64	0.79	0.90
Keara Lake - 2009	0.52	0.49	0.65	0.80	0.91
513 Lake - 2010	0.65	0.50	0.65	0.80	0.91
Halji Lake - 2011	0.79	0.88	0.95	0.98	1.00
382 Chorabari Lake - 2013	0.59	0.73	0.85	0.93	0.98

383 **3.3 Criteria thresholds sensitivity analysis**

384 The results of this second sensitivity analysis are shown in Table 5. Respectively, Rows A and B indicate  
 385 the number of lakes that change risk class and change risk classification confidence level when each  
 386 criterion threshold is modified. Several criteria lead to little or no change to the number of lakes that  
 387 are re-classified when their thresholds are modified, and only minor changes in the percentage of  
 388 confidence in each risk class. These are intense precipitation events (TR.2), distance between lake and  
 389 steepest slope (ME.4), and distance between lake and glacier (ME.5). Altering thresholds for high

390 temperature events (TR.3), GLOF travel distance (SR.1), potential loss of human life (IM.1), and  
391 steepest slope surrounding the lake (ME.3), lead to a shift of up to three lakes from low to medium  
392 and from medium to high risk, and a change of confidence levels for up to four lakes. Threshold  
393 alterations for lake volume (SR.2) and regional seismic activity (TR.1) resulted in the greatest shift in  
394 lake risk classification, with three and four lakes respectively changing from medium risk to high risk,  
395 as well as four and eight lakes changing confidence levels respectively for SR.2 and TR.1.

396 Columns C and D in Table 5 illustrate, respectively, the number of times each lake changes risk class  
397 and confidence level within a class when a criterion threshold is changed. In summary, Maud lake,  
398 Godley lake and Chholamo all remain as low-risk throughout the process, but Lake 0071 shifts once  
399 from low risk to medium risk. Hanpi k'ocha and Keara lake change from medium to high risk twice,  
400 Passu lake three times, and lake 513 five times. Hence, Passu lake and lake 513 appear to be  
401 particularly sensitive to certain individual criteria thresholds being changed. Confidence levels remain  
402 stable in most cases, with some exceptions; Chholamo and Keara lakes undergo a shift in class  
403 confidence level once, and Gopang Gath, Schako Tsho, Flatbreen Lake and Chorabari lake twice.  
404 Furthermore, the confidence level changes three times for Maud lake and Halji lake, and four times  
405 for Godley lake and Spong Tongpo. Overall, the model results remain robust when thresholds are  
406 changed, but some lakes are identified through sensitivity analysis as being particularly sensitive, and  
407 hence possibly worthy of careful attention in any risk management decisions or actions.

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411 Table 5 - Sensitivity analysis of individual criteria as compared to results before sensitivity analysis (as in Table 3). Decimal percentages indicate the level of confidence that a lake belongs  
 412 to the specific risk class (Low risk = Green, Medium risk = Orange, High risk= Red). We also indicate the number of lakes that change A) risk class or B) confidence level for each criterion  
 413 threshold change, and the number of times a lake changes C) risk class or D) confidence level for each criterion threshold change.

Dangerous lakes - literature	Results before sensitivity (as in table 3)											
	TR.1	TR.2	TR.3	ME.3	ME.4	ME.5	SR.1	SR.2	IM.1	C	D	
Maud Lake	0.97	0.94	0.97	0.91	0.94	0.97	0.97	0.97	0.97	0.97	0	3
Godley Lake	0.89	0.81	0.89	0.77	0.81	0.80	0.89	0.89	0.89	0.89	0	4
Chholamo	0.89	0.81	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0	1
Lake 0071	0.58	0.58	0.58	0.58	0.58	0.58	0.65	0.58	0.58	0.58	1	0
Hanpi k'ocha	0.62	0.58	0.62	0.62	0.62	0.62	0.62	0.58	0.62	0.62	2	0
Gopang Gath	0.92	0.81	0.92	0.92	0.92	0.92	0.95	0.92	0.92	0.92	0	2
Spong Tongpo	0.70	0.53	0.70	0.52	0.70	0.62	0.70	0.70	0.52	0.70	0	4
Schako Tsho	0.78	0.91	0.78	0.78	0.78	0.78	0.78	0.78	0.78	0.91	0	2
Imja Tsho	0.78	0.92	0.92	0.92	0.78	0.92	0.92	0.92	0.92	0.92	0	0
Tsho Rolpa	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0	0
Thulagi Tsho	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0	0
Dig Tsho	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0	0
Lower Barung Tsho	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0	0
Ludming Tsho	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0	0
Chamlang South Tsho	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0	0
Chamlang North Tsho	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0	0
Selected GLOF events	Results before sensitivity (as in table 3)											
	TR.1	TR.2	TR.3	ME.3	ME.4	ME.5	SR.1	SR.2	IM.1	C	D	
Flatbreen Lake - 2004	0.77	0.77	0.77	0.54	0.77	0.77	0.77	0.57	0.77	0.77	0	2
Passu Lake - 2007	0.65	0.58	0.65	0.58	0.65	0.65	0.65	0.58	0.65	0.65	3	0
Keara Lake - 2009	0.52	0.58	0.52	0.52	0.52	0.52	0.59	0.61	0.52	0.52	2	1
513 Lake - 2010	0.65	0.58	0.65	0.58	0.65	0.65	0.59	0.58	0.58	0.58	5	0
Halji Lake - 2011	0.79	0.79	0.92	0.79	0.79	0.79	0.79	0.91	0.92	0.92	0	3
Chorabari Lake - 2013	0.59	0.79	0.59	0.59	0.79	0.59	0.59	0.59	0.59	0.59	0	2
<b>A</b>	<b>4</b>	<b>0</b>	<b>1</b>	<b>1</b>	<b>0</b>	<b>0</b>	<b>3</b>	<b>3</b>	<b>1</b>			
<b>B</b>	<b>8</b>	<b>1</b>	<b>3</b>	<b>4</b>	<b>1</b>	<b>0</b>	<b>1</b>	<b>4</b>	<b>2</b>			

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415 **3.4 Application to a data-scarce region: the Bolivian Andes**

416 Here, we apply the MCDA method to glacial lakes of the Bolivian Andes, which is a region where GLOF  
 417 risk has not yet been studied in detail, and where there are a range of lake types, and very little  
 418 information about the nature of the lakes or the environment within which they are situated. Cook et  
 419 al. (2016) performed a rudimentary assessment of the GLOF threat posed by Bolivian glacial lakes;  
 420 their work amounts to the completion of Steps 1 and 2 in Figure 2. They identified 137 lakes in total;  
 421 from these lakes, 25 had population downstream and therefore required further investigation. This  
 422 list includes a mix of moraine-dammed and bedrock-dammed lakes, although an ice-dammed lake at  
 423 Keara burst in 2009, and is featured in our earlier model results. To assess GLOF risk for these 25 lakes,  
 424 the  $\lambda$ -cutting level is set at 0.65 and the criteria thresholds are kept at their initial values. Qualitative  
 425 values for each criterion were assigned for the lakes (see also Supplementary Data - Appendix B, Table  
 426 B.3)

427 Table 6 illustrates the results of the Bolivian GLOF risk assessment. Overall, one lake is identified as  
 428 high risk (Murarata – Laguna Arkhata), and two lakes are identified as medium risk (Apolobamba –  
 429 Pelechuco; Real – Laguna Glaciar). The remainder are graded as low risk.

430 **Table 6 – Risk levels for potentially dangerous lakes in the Bolivian Andes as identified by Cook et al. (2016). Decimal**  
 431 **percentages indicate the level of confidence that a lake belongs to the specific risk class (Low risk = Green, Medium risk =**  
 432 **Orange, High risk= Red).**

Lakes	Coordinates in UTM		Risk level
Apolobamba - Puina	19 L	476504 8384832	0.58
Apolobamba - Pelechuco	19 L	481205 8365591	0.84
Apolobamba - Hilo Hilo 1	19 L	492850 8354529	0.79
Apolobamba - Hilo Hilo 2	19 L	487996 8349572	0.91
Apolobamba - Hilo Hilo 3	19 L	487666 8349316	0.78
Apolobamba - Puyo Puyo	19 L	486275 8351196	0.97
Apolobamba - Taypi Cayuma 1	19 L	491182 8343142	0.92
Apolobamba - Taypi Cayuma 2	19 L	492072 8340807	0.94
Apolobamba - Cholina Cholina 1	19 L	497085 8337363	0.78
Apolobamba - Cholina Cholina 2	19 L	498284 8335884	0.94
Real - Laguna Glaciar	19 L	547085 8249728	0.81
Real - Cocoyo 1	19 L	556846 8251418	0.94
Real - Cocoyo 2	19 L	559120 8249880	0.97
Real - Cocoyo 3	19 L	560553 8247486	0.58
Real - Rinconada 1	19 L	552071 8244232	0.58
Real - Rinconada 2	19 L	550069 8242190	0.58
Real - Laguna Wara Warani	19 K	567694 8222503	0.79
Real - Umopalca	19 K	584186 8220965	0.58
Real - Condoriri	19 K	578927 8210860	0.98
Real - Comunidad Pantini	19 K	612872 8182149	0.97
Murarata - Laguna Arkhata	19 K	624521 8172040	0.58
Tres Cruces - North	19 K	670245 8126070	0.91
Tres Cruces - Mining camp west	19 K	674446 8120893	0.57
Tres Cruces - Mining camp east	19 K	678278 8121207	0.77
Tres Cruces - Laguna Huallatani	19 K	675910 8118767	0.77

433

434 **4. Discussion**

435 **4.1 Comparisons with existing GLOF hazard and risk assessments**

436 We assessed the level of GLOF risk for 16 lakes that had been identified in previous studies as  
437 representing a threat to downstream communities or infrastructure and found that our results were  
438 broadly consistent with those previous studies (Table 3). This is encouraging because our risk  
439 assessment model has been applied here to a range of regions and dam-types, whereas previous  
440 studies have generally focused on specific regions or specific lake or dam contexts. This widely  
441 applicable assessment is useful from a risk-management perspective because many glacierised  
442 landscapes contain a range of glacial lake types, and our model allows all lakes to be evaluated  
443 simultaneously. Specifically, we achieved the same results for Lake Hanpi K'ocha as did Frey et al.  
444 (2016), even though their risk assessment was based on field study and the use of criteria that cannot  
445 be evaluated in a desk-based study. Allen et al. (2009) focused only on hazard analysis rather than risk  
446 or impact assessment, but their outburst flood modelling results for Maud Lake and Godley Lake do  
447 not show any potential downstream impacts, which is consistent with the low risk rating from our  
448 MCDA method. Aggarwal et al. (2017) estimated Chholamo to represent a low GLOF susceptibility and  
449 Lake 0071 to represent a medium GLOF susceptibility, but both of those lakes are not upstream of  
450 important infrastructure or population, and hence are rated as low risk in our assessment. Worni et  
451 al. (2013) estimated that Gopang Gath and Spong Tongpo pose a medium level of risk, which agrees  
452 with our results. This is due mostly to the relatively low downstream population and the long runout  
453 distances required for flood impact to villages. In addition, triggering factors (TR.1, 2, 3) are graded as  
454 low in this area of the Himalaya. Worni et al. (2013) also assessed Schako Tsho and found that it posed  
455 a high level of risk, which agrees with our results. This rating is driven by intense precipitation events,  
456 steep slopes in close proximity to the lake, and the presence of nearby communities downstream.  
457 Rounce et al. (2016) assessed eight large Nepalese lakes with significant populations or infrastructure  
458 downstream. All eight lakes are in close proximity to steep slopes, most are in contact with parent  
459 glaciers, and there are potential triggers including seismic activity and intense precipitation events.  
460 The authors assessed the GLOF risk of most lakes to be high, with the exception of Imja Tsho, which  
461 was graded as medium risk, and Lower Barung Tsho, which was graded as very high risk. The authors  
462 underline that Imja Tsho will become high risk in the next 10 to 20 years because it is growing rapidly.  
463 Our model largely agrees with these results by classifying all of these lakes as high risk.

464 **4.2 Comparisons of model results with GLOF-generating lakes**

465 Table 3 also presents pre-GLOF risk assessments for seven lakes that have already generated GLOFs.  
466 This selection of GLOF-generating lakes comprises a mixture of ice, moraine and bedrock dams located  
467 in different regions around the world. Flatbreen lake burst in 2004 and generated a debris flow that

468 reached the valley bottom ~1000m below the lake (Breien et al., 2008). This lake is graded as low risk  
469 (a result that is sustained throughout the sensitivity analyses – Tables 4 and 5) due to both  
470 downstream impact parameters (IM.1 and IM.2) falling into the low impact category - there is no  
471 significant population or infrastructure in the immediate floodpath downstream (except farmland and  
472 a minor road). The Passu lake, Keara lake and lake 513 GLOF events are known to have damaged roads  
473 or bridges, or to have increased downstream sedimentation causing malfunction of water-treatment  
474 plants or damage to agricultural land (Ashraf et al., 2012; Carey et al., 2012; Hoffmann and  
475 Wegenmann, 2013; Klimeš et al., 2014; Vilímek et al., 2015). Nevertheless, they did not cause any  
476 casualties or fatalities. These factors are key drivers of the medium-risk classification from our MCDA  
477 method (Table 3). In contrast, Halji and Chorabari lakes are situated in relatively close proximity to  
478 downstream infrastructure and relatively high population numbers meaning that the overall risk was  
479 graded as high.

#### 480 **4.3 Potentially dangerous glacial lakes of the Bolivian Andes**

481 GLOF risk was assessed for 25 lakes in the Bolivian Andes (Table 6). This represents the sort of situation  
482 where our model would be particularly valuable, i.e. in a region where GLOF risk has not yet been  
483 studied in detail, there are a range of lake types that need to be assessed simultaneously, and there  
484 are few data or observations to base decisions upon.

485 Our MCDA method reveals that 22 lakes represent low risk, mostly because of the low levels of  
486 downstream population and infrastructure, as well as the presence of bedrock dams, which are  
487 regarded as being more stable, and small estimated lake volumes. In addition, the glacierised area of  
488 the Cordillera Oriental, where these lakes are situated, is not a highly seismically active zone.  
489 Nevertheless, three lakes pose a more significant potential threat to downstream areas: the lake  
490 situated upstream from the village of Pelechuco, as well as Laguna Glaciar and Laguna Arkhata.  
491 Pelechuco lake and Laguna Glaciar are classified in our model as medium risk lakes with a high level  
492 of confidence, as shown in Table 6 (0.84 and 0.81 respectively). This can be explained by the high  
493 population downstream, and both seem to be susceptible to GLOFs since they are in contact with their  
494 parent glacier, and surrounded by steep slopes. Laguna Arkhata is the only lake classified as high risk,  
495 with a confidence level of 0.58. This is mostly due to its large size, the large population downstream,  
496 steep slopes surrounding the lake, and contact between the lake and parent glacier. Having completed  
497 the MCDA method, future work can now be directed more confidently toward intensive study of the  
498 three most dangerous lakes.

499

#### 500 **4.4 MCDA model sensitivity**

501 To our knowledge, we have undertaken the first sensitivity analysis of any GLOF risk or hazard  
502 assessment model. Sensitivity analysis allows the strength of the model to be assessed, and the  
503 certainty of lake risk classification to be explored. Sensitivity analysis is readily undertaken in the  
504 SMAA-TRI software, which is a key benefit of our approach.

505 All medium and high-risk lakes have at least three criteria rated as high risk (except Gopang Gath,  
506 which possesses only two high risk criteria), which causes them to remain in or switch into a high-risk  
507 category when the cutting level is increased from 0.65 to 0.85 (Table 4). Low-risk lakes and Gopang  
508 Gath stand out in Table 4 because their risk classification remains stable for all or most of the  
509 sensitivity tests. All low-risk lakes are dominated by low-risk ratings for all criteria so that even as the  
510  $\lambda$ -cutting level is increased (i.e. the model is made more conservative), their overall risk level remains  
511 low. Gopang Gath, on the other hand, has a high number (9 out of 13) of criteria rated as medium risk,  
512 and only two high risk and two low-risk criteria. Therefore, the lake has an overall rating of medium  
513 risk until the cutting level is raised to 0.85, where even then the high-risk classification has only a  
514 modest confidence value of 0.44 (with low risk at 0.28 and medium risk at 0.28) (Table 5). Crucially,  
515 sensitivity analysis can be used, as it is here, to identify those lakes that remain within the same risk  
516 class as the cutting level is increased, which gives confidence to the user in making risk management  
517 decisions (e.g. whether additional monitoring or remediation would be required), or to identify cases  
518 where lakes are close to a higher risk boundary after the initial assessment with a lower cutting level  
519 (i.e. lakes that switch class as the cutting level is increased), and to evaluate the confidence level of  
520 the risk classifications. Overall, a  $\lambda$ -cutting level of 0.65 should be sufficiently robust for general use or  
521 initial risk assessment.

522 One of the key benefits of the MCDA approach is the use of the Description Problem approach to  
523 decide upon appropriate GLOF risk assessment criteria. However, the choice of thresholds for each  
524 criterion remains uncertain in some cases (see also Supplementary Data - Appendix A). Hence, we also  
525 explored the effect of changing the threshold values for the high-risk category of each criterion (Table  
526 5). For the most part, Table 5 illustrates that alteration of the thresholds for most criteria yields  
527 relatively few changes in risk categorization for each lake in our sample. This is due in large part to the  
528 fact that many of the lakes in our sample already fall into the high-risk category for each criterion,  
529 meaning that a relaxation of the criteria for high risk has little effect on the results. Nevertheless, there  
530 are a few notable exceptions. By relaxing the seismic activity (TR.1) high-risk threshold, 4 lakes are re-  
531 graded as high risk. However, this probably constitutes an unrealistic reclassification whereby  
532 mountain ranges with modest or low seismic activity are ascribed a higher risk rating. Risk managers  
533 and geoscientists should be able to gain sufficiently accurate information on regional seismic activity

534 that they can attain appropriate thresholds and classifications, and the sensitivity analysis here gives  
535 us greater confidence that our original risk thresholds were already robust and realistic. Another  
536 exception is lake volume (SR.2) where the relaxation of the high-risk threshold results in three lakes  
537 being re-graded as high risk. Lake volume is an example of a criterion where it can be hard to  
538 determine where the thresholds should lie – in essence, it is hard to say what constitutes a large,  
539 medium or small lake. Our original lake volume classification (Table 2) is derived from a global glacial  
540 lake dataset (Cook and Quincey, 2015) that includes water bodies ranging in size from supraglacial  
541 ponds ( $0.1 \times 10^6 \text{ m}^3$ ) to very large lakes ( $770 \times 10^6 \text{ m}^3$ ) (see also Supplementary Data - Appendix A).  
542 Our thresholds were informed by plotting a frequency distribution of the dataset presented in Cook  
543 and Quincey (2015). By relaxing the high-risk threshold, any lake with a size of  $1 \times 10^6 \text{ m}^3$  or larger is  
544 classified as high risk, which captures most of the lakes in our sample set. Given that the lake might  
545 not drain completely during a GLOF event, this revised threshold might be regarded as being overly  
546 conservative. Again, our sensitivity analysis gives us confidence that our original threshold was  
547 appropriate. Finally, relaxation of the GLOF travel distance high-risk threshold (SR.1) also causes three  
548 lakes to be re-graded as high risk. Our original threshold system was informed by previous studies  
549 (Huggel et al., 2002; Huggel and Hegglin, 2008) that adopted an empirical approach to defining the  
550 critical slope for clear water and debris-laden GLOF runout. Given this empirical basis, our sensitivity  
551 analysis here merely explores a very conservative threshold system, although risk managers may wish  
552 to use this system if there are large uncertainties about topography or the nature of the potential  
553 flood (e.g. whether sediment is likely to be entrained into a debris flow).

554 A small number of lakes, including Lake 513 and Passu Lake, are readily reclassified when the high-risk  
555 threshold is relaxed for some criteria (including TR.1, ME.3, SR.1, SR.2, IM.1). These lakes may need  
556 particular attention from risk managers, as they appear to be borderline cases. Fortunately, sensitivity  
557 analysis is able to reveal such cases.

#### 558 **4.5 The use of MCDA in GLOF risk assessments**

559 Several previous studies (Huggel et al., 2004; Bolch et al., 2008; Mergili and Schneider, 2011; Emmer  
560 and Vilimek, 2013; Worni et al., 2013; Rounce et al., 2016) have provided important frameworks by  
561 which to assess GLOF hazard or risk. Since these are typically designed for particular sites or regions,  
562 and/or for specific lake types, they are already likely to provide robust risk and hazard assessments in  
563 those situations. However, risk managers in some regions may be presented with situations where a  
564 range of lake types may exist, and it is desirable to assess the relative level of hazard or risk between  
565 these lakes simultaneously. For example, a risk or hazard assessment designed for moraine-dammed  
566 lakes cannot necessarily be used to assess the risk or threat posed by ice-dammed or bedrock-  
567 dammed lakes. In this study, we have presented an MCDA approach that offers several key benefits

568 for GLOF hazard and risk assessment that make it particularly useful in such situations. In common  
569 with some, but not all, previous studies (Fujita et al., 2008; Bolch et al., 2011; Aggarwal et al., 2016;  
570 Petrov et al., 2017), our MCDA approach uses free and widely available datasets or inputs, and there  
571 is no need for the inclusion of any field data – all of the information can be gathered and processed  
572 remotely as a desk-based study. Certainly, additional field-based data or higher resolution satellite  
573 imagery or elevation data would be advantageous, and could be incorporated into the MCDA model,  
574 but we have shown here, through comparisons with previous studies and sensitivity analyses, that this  
575 approach is already robust. Our approach would be particularly useful in serving as an initial survey  
576 for an area with several lake types in order to identify particularly dangerous lakes that might require  
577 further detailed study (e.g. fieldwork, hydrological modelling, remediation, monitoring, etc.). The  
578 MCDA approach presented here is a two-stage process, whereby a Description Problem is addressed  
579 first, before a Sorting Problem is completed. The formulation of the Description Problem represents  
580 another key benefit compared to previous GLOF risk and hazard assessments. Firstly, and in common  
581 with some previous reviews on GLOF initiation and impacts (e.g. Emmer and Vilimek, 2013; Rounce et  
582 al., 2016), it forces a comprehensive review of all factors that could drive a glacial lake towards  
583 becoming dangerous (Fig. 1 and Tables 1 and 2). Crucially, however, the principles of MCDA (section  
584 2.1) mean that the criteria selected to assess GLOF risk are exhaustive, non-redundant, and consistent.  
585 Many previous studies have kept, for example, one composite criterion instead of splitting it into  
586 multiple criteria, therefore potentially biasing the analysis.

587 The use of the SMAA-TRI software has some specific advantages. Firstly, it is freely available, but it is  
588 also straightforward to use, and it has a means of testing the strength of results through the  
589 generation of confidence measures and sensitivity analyses, as outlined in this study. Further,  
590 although we have opted for a Sorting Problem approach, the use of SMAA-2 (which can be found in  
591 the same download package; <http://smaa.fi/>) allows the construction of a Ranking Problem, which  
592 may be useful for other practitioners with different requirements.

593 Our MCDA approach, through the construction of a Description Problem (section 2.2), streamlines the  
594 wide array of criteria that have been used previously to assess GLOF risk. Nonetheless, since our  
595 approach offers a rapid, first pass assessment of GLOF risk, the final 13 criteria used inevitably ignore  
596 some criteria that cannot be assessed remotely (e.g. vulnerability factors, specific details about the  
597 nature of the dam, etc.). Hence, there remain situations where it would be advantageous to use  
598 existing GLOF risk assessments that have been tailored to specific lakes, regions or contexts, or where  
599 field data are available to be incorporated into the risk assessment to address particular criteria.

600 There remain a number of challenges for those constructing and using GLOF risk and hazard  
601 assessments. Firstly, the thresholds used to define risk categories are uncertain. For the most part, we  
602 have borrowed thresholds for each criterion based on previous work (see also Supplementary Data -  
603 Appendix A), and this then reflects some degree of consensus among the GLOF risk community about  
604 how to assess GLOF risk. But some values might be questioned. For example, how big is a big (high-  
605 risk) lake? How steep is a steep (high-risk) slope that could shed ice or rock mass movements into the  
606 lake? Should we use potential loss of life thresholds that could be applicable to mass casualty events,  
607 such as tsunamis and earthquakes, where many thousands of people could lose their lives, or should  
608 we use lower thresholds considering that most GLOF-affected environments are relatively sparsely  
609 populated? Another unsolved problem is the weighting for each of the criteria used. At this stage, it is  
610 impossible to tell whether some criteria are more important than others, with the exception perhaps  
611 of loss of life and damage to infrastructure.

## 612 **5. Conclusion**

613 For the first time, we have undertaken a risk assessment for glacial lake outburst floods (GLOFs) using  
614 a Multi-Criteria Decision Analysis (MCDA) approach. MCDA has been applied to several natural hazard  
615 and risk contexts, but never before to GLOFs. Whilst several previous studies have outlined GLOF  
616 hazard and risk assessment procedures, we argue that the MCDA method has a number of benefits to  
617 offer. The MCDA approach (1) uses freely and widely available data inputs and software, without the  
618 requirement for field-based study; (2) can be applied across a range of glacial lake contexts (ice-  
619 dammed, moraine-dammed, etc.) simultaneously, and to any region of the world; (3) enables  
620 researchers to make a first-pass analysis of potentially dangerous lakes objectively before committing  
621 to further investigation (e.g. field work, remote sensing data analysis); and (4) readily permits  
622 sensitivity testing of the model. Crucially, the first stage of the MCDA approach (the Description  
623 Problem) involves the determination of appropriate criteria by which to define risk. The principles of  
624 MCDA require the use of exhaustive, non-redundant, and consistent criteria, which can be regarded  
625 as a key benefit of this approach. For example, previous assessment procedures have sometimes  
626 double-counted, ignored, or selected criteria subjectively or non-transparently (McKillop and Clague,  
627 2007a,b).

628 We assessed the risk of 16 potentially dangerous glacial lakes as well as 6 lakes that have already  
629 generated GLOFs in the past (between 2004 and 2013). Our results for the 16 extant lakes compare  
630 favourably with previous risk and hazard assessments, which have generally focused on specific  
631 regions or glacial lake contexts. This indicates that our MCDA model can be applied in a range of  
632 contexts globally. Further, we undertook sensitivity analyses of our model to explore the robustness

633 of results and model assumptions. To our knowledge, this is the first time sensitivity analysis has been  
634 performed for a GLOF risk or hazard assessment model. Two sensitivity analyses were undertaken. In  
635 the first, the proportion of criteria that need to be graded as 'high risk' in order to grade the overall  
636 risk as 'high' was relaxed (the so-called ' $\lambda$ -cutting level'). This identified several lakes that remain  
637 within the same risk class as this cutting level is increased, which gives confidence to the user in making  
638 risk management decisions about those lakes. The second sensitivity test involved relaxing the  
639 threshold for 'high risk' for each criterion. This generally revealed that the original risk thresholds used  
640 here were robust, although some lakes were identified that might warrant further study because they  
641 changed readily to a higher risk class. We applied the tested method on 25 glacial lakes in the data-  
642 scarce Bolivian Andes, and found that 22 of these lakes represent low risk, and therefore do not  
643 currently require further attention. Nevertheless, further detailed investigation or action is required  
644 for two lakes rated as medium risk (Pelechuco, Laguna Glaciar), and one lake rated as high risk (Laguna  
645 Arkhata).

646 We suggest that our MCDA approach would be best suited to identifying potentially dangerous lakes  
647 in regions where a range of glacial lake types may exist, such as demonstrated here for the Bolivian  
648 Andes. Our method allows the relative risk of these different lakes to be assessed simultaneously, and  
649 takes account of both GLOF susceptibility and potential impacts.

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928 **Supplementary data**

929 **Appendix A - Criteria description and threshold definition**

930 **Triggers**

931 **Regional seismic activity (TR.1)**

932 Regional seismic activity has been recognised by many authors as a key trigger of dam collapse, as well  
933 as generation of rockfalls, landslides, snow avalanches and icefalls (Zapata, 2000; Mergili and  
934 Schneider, 2011; Emmer and Vilimek, 2013; Rounce et al., 2016). One of the clearest global measures  
935 is the maximum possible Peak Ground Acceleration PGAm<sub>ax</sub> (m s<sup>-2</sup>) which can be obtained for a global  
936 scale from the Global Seismic Hazard Map (<http://gmo.gfz-potsdam.de>). The thresholds set by Mergili  
937 and Schneider (2011) are divided into low (<0.5 m/s<sup>2</sup>) and high (>0.5 m/s<sup>2</sup>) seismic hazard. Since our  
938 criteria are divided into three classes, and we aim to capture seismic hazard for any situation globally,  
939 we decided to also use the upper threshold set by Shi and Kasperson (2015), and therefore we  
940 extended the high-risk category to 3.9 m/s<sup>2</sup> and added the medium-risk class.

941 **Intense precipitation events (TR.2) and high temperature events (TR.3)**

942 Intense precipitation events and high temperature events have been combined in previous studies as  
943 the 'hydrometeorological' situation (Huggel et al., 2004; Wang et al., 2011), and such events have the  
944 capacity to trigger mass movements into a lake. Nevertheless, this does not offer the possibility to  
945 score each element of the criterion individually, indicating non-exhaustiveness. After splitting them  
946 into two separate criteria, the use of two global BIOCLIM indicators (BIO 4 - temperature seasonality;  
947 BIO 15 - precipitation seasonality) were considered as the most appropriate surrogates. Our rationale  
948 was that a more varied seasonal cycle in precipitation or temperature would be a reasonable proxy  
949 for how intense the precipitation or temperature events are. Precipitation seasonality is the measure  
950 of the variation in monthly precipitation totals over the course of the year. This index is the ratio of  
951 the standard deviation of the monthly total precipitation to the mean monthly total precipitation (also  
952 known as the coefficient of variation) and is expressed as a percentage; larger percentages represent  
953 greater variability of precipitation. We divided the three classes into <50% (low risk), which represents  
954 precipitation occurring roughly equally throughout the year, 50-100% (medium risk) representing  
955 seasonal precipitation, and >100% (high risk) which indicates precipitation occurring in less than three  
956 months in the year. Temperature seasonality indicates the amount of temperature variation over a  
957 given year (or averaged years) based on the standard deviation (variation) of monthly temperature  
958 averages. It is a measure of temperature change over the course of the year. The larger the standard  
959 deviation, the greater the variability of temperature. We have divided into three classes: <50% (low

960 risk), 50-100% (medium risk), >100% (high risk). For extra information on these variables visit:  
961 <https://pubs.usgs.gov/ds/691/ds691.pdf>

## 962 **Mechanisms**

### 963 **Dam freeboard (ME.1)**

964 Dam freeboard is one of the most commonly used factors to determine the possibility of a wave  
965 overtopping any type of dam. Nevertheless, the exact height of the freeboard is difficult to measure  
966 from satellite data (Worni et al., 2013). We set the thresholds here to low (>15 m), medium (15-5 m)  
967 and high risk (<5 m) according to previous studies that have evaluated freeboard from open-source,  
968 high-resolution satellite imagery (Wang et al., 2012; Worni et al., 2013).

### 969 **Dam type (ME.2)**

970 Lake dam type has been considered as one of the main factors for outburst probability (Huggel et al.,  
971 2004; Mergili and Schneider, 2011; Emmer and Vilímek, 2013). Carrivick and Tweed (2016) observed  
972 that, in terms of historical and modern glacier floods occurring worldwide, 70 % are from ice-dammed  
973 lakes, 9 % are from moraine-dammed lakes, 16 % are from an unknown dam type/trigger, and 3 % are  
974 triggered by volcanic activity (nearly all of them taking place in Iceland). In another study, Emmer et  
975 al. (2016b) summarized more than 500 GLOF events based on scientific research articles, non-scientific  
976 reports and regional studies. They identified 380 GLOFs from ice-dammed lakes, 130 GLOFs from  
977 moraine-dammed lakes and several GLOFs originating from bedrock-dammed lakes or lakes with  
978 combined dam. Even though moraine dammed lakes have been deadlier than ice-dammed lakes (e.g.  
979 Lake Palcacocha in 1941), the potential loss of human life remains a separate criterion and we only  
980 examine here the stability of the dam (to avoid double-counting criteria). Hence, there are three  
981 classes: ice-dam (high risk), moraine-dam (medium risk), and bedrock dam (low risk) which are also  
982 used in previous studies (Huggel et al., 2004; Worni et al., 2013; Wang et al., 2013).

### 983 **Steepest slope surrounding lake (ME.3)**

984 Mass movements entering a glacial lake are the main cause leading to GLOFs (Worni et al., 2013;  
985 Rounce et al., 2016). Steep slopes promote mass movements, which in turn can impact the lake and  
986 generate a flood wave that overtops or destroys the natural dam. Areas with a slope greater than 30°  
987 are susceptible to rock avalanches or landslides (Alean, 1985; Bolch et al., 2011; Rounce et al., 2016).  
988 Moreover, according to Alean (1985), temperate glaciers have been found to produce ice avalanches  
989 from a minimum slope of 25°, and cold-based glaciers from 45°. Therefore, we decided to consider  
990 25° as the minimum threshold slope that can generate mass movements into a lake. Any lake that is  
991 not surrounded by a slope of at least 25° is not considered in the study. In addition, previous studies

992 have considered only lakes within 500m of a glacier to be potential GLOF sources (e.g. Wang et al.,  
993 2011, 2015). Therefore, lakes that are further than 500m from a slope, or closer than 500m from a <  
994 25° slope are not considered in this study. We defined three classes: <30° slope (low risk), 30-45° slope  
995 (medium risk) and >45° slope (high risk). The high-risk threshold is lowered to 30° for the sensitivity  
996 analysis in order to observe potential differences and risk class changes for the studied lakes.

997 **Distance between lake and steepest slope (ME.4) & distance between lake and parent glacier (ME.5)**

998 Distance and slope between the lake and parent glacier determine the possibility of calving into the  
999 glacial lake (Wang et al., 2011). The most well-known example is the one from Lake Palcacocha in  
1000 1941, where a huge chunk of the adjacent glacier fell into the lake causing an outburst flood, severely  
1001 damaging the city of Huaraz, and causing as many as 6000 deaths (Carey et al., 2012; Somos-  
1002 Valenzuela et al., 2016). Previous studies have considered lakes within 500m of a glacier to be  
1003 potential GLOF sources (e.g. Wang et al., 2011; Wang et al., 2015; Cook et al., 2016). Both lakes within  
1004 500m of a glacier could be impacted by ice and snow avalanches, which could also generate  
1005 overtopping waves (Alean, 1985; Rickenmann, 1999, 2005). In addition, in the absence of detailed  
1006 modelling of mass movement runout distances, we considered any proglacial lake within 500 m of a  
1007 slope to be potentially dangerous, although we emphasise that the selection of these values is  
1008 somewhat subjective. Overall, for both criteria (ME.4 & ME.5), we defined three risk classes as follows:  
1009 500 - 250m (low risk), 250 - 10m (medium risk), 10m - contact with lake (high risk).

1010 **Parent glacier snout steepness (ME.6)**

1011 For a parent glacier situated in proximity to a lake, a steep glacier snout can lead to enhanced levels  
1012 of ice calving into the lake, which raises the risk of a GLOF (e.g. Grabs and Hanisch, 1993; Zapata, 2000;  
1013 Wang et al., 2011). Following the classification of Wang et al. (2011) and Emmer et al. (2015) we derive  
1014 three classes in parent glacier snout steepness: <15° (low risk), 15°-25° (medium risk) and >25° (high  
1015 risk).

1016 **Flood wave size/runout**

1017 **Travel distance of GLOF (SR.1)**

1018 One of the main parameters for GLOF risk assessment is to estimate whether the flood wave can reach  
1019 downstream communities. For this estimation, a 'worst-case' approach is followed (Huggel et al.  
1020 2002). Studies have analysed the runout characteristics of debris flows from glacier/moraine-dammed  
1021 lakes in the European Alps. It has been found that debris flows generally abate when they reach a  
1022 downstream average slope of 11° and clean flows when they reach 3° (Haeberli, 1983; Huggel et al.,  
1023 2002; Hegglin and Huggel, 2008). The average slope angle is thereby defined as the slope of a line

1024 between the start and end point of an outburst event. Therefore, in this study we used the thresholds  
1025 of 3-7° (low risk), 7-11° (medium risk), >11° (high risk). We encourage the use of the Modified Single-  
1026 Flow direction model (MSF) for experienced users (Huggel et al., 2003), and a new version of this has  
1027 been developed by Rounce et al. (2017b). Less experienced modellers may use Google Earth to find  
1028 the average slope between the lake and potentially exposed communities or infrastructure.

#### 1029 **Lake volume (SR.2)**

1030 Lake volume is regarded as a significant criterion since it determines the maximum amount of water  
1031 that could be released downstream. Our original lake volume classification is derived from a global  
1032 glacial lake dataset (Cook and Quincey, 2015) that includes water bodies ranging in size from  
1033 supraglacial ponds ( $0.1 \times 10^6 \text{ m}^3$ ) to very large lakes ( $770 \times 10^6 \text{ m}^3$ ). Our thresholds were informed by  
1034 plotting a frequency distribution of the dataset presented in Cook and Quincey (2015). Consequently,  
1035 we derived three classes of risk:  $<1 \times 10^6 \text{ m}^3$  (low risk),  $1 \times 10^6 \text{ m}^3 - 10 \times 10^6 \text{ m}^3$  (medium risk) and  $10 \times$   
1036  $10^6 \text{ m}^3 - 100 \times 10^6 \text{ m}^3$  (high risk). Alternatively, one could also apply the Potential Flood Volume (PFV)  
1037 method of Fujita et al. (2013) for moraine-dammed lakes where appropriate data are available.

#### 1038 **Impact**

##### 1039 **Potential loss of human life (IM.1) & potential loss of infrastructure (IM.2)**

1040 GLOF risk implies that there must be downstream impacts such as potential loss of human lives and  
1041 infrastructure. Glacier floods have directly caused at least: 7 deaths in Iceland, 393 deaths in the  
1042 European Alps, 5745 deaths in South America and 6300 deaths in central Asia (Carrivick and Tweed,  
1043 2016). It is important to know the number of people under potential threat beforehand in order to  
1044 suggest the appropriate measures. In order to rank the classes of risk by population affected we used  
1045 thresholds set by international sources (Omelicheva, 2011; EM-DAT/Emergency Events Database) :  
1046 <10 people (low risk), 10-1000 people (medium risk) and >1000 people (high risk). As for  
1047 infrastructure, we graded the severity from high, where a hydraulic dam, mining camp or a  
1048 historic/heritage site is under threat, to low, where damage to agricultural fields or dirt roads may  
1049 indirectly affect the local population. It is important to use the best population data available. If no  
1050 data exist, we suggest to estimate population using a combination of Google Earth (to identify number  
1051 of households) and the United Nations Statistics Division (UNSD;  
1052 <https://unstats.un.org/unsd/demographic/>) data for people per household in the country of interest.

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1060 **Appendix B - Criteria values for lake evaluation**

1061 **Table B.1 - Quantitative criteria evaluation for the global lake dataset. For the criteria ME.1, ME.6 and IM.1 it is impossible to give an exact value due to the resolution of Google Earth**  
 1062 **imagery, or due to missing information. For the criterion ME.3, Google Earth does not let the user to identify the exact value of slopes >45 degrees.**

Dangerous lakes - literature		Coordinates in UTM		TR.1	TR.2	TR.3	ME.1	ME.2	ME.3	ME.4	ME.5	ME.6	SR.1	SR.2	IM.1	IM.2
Maud lake	59 G	459482	5185818	3.4	13	43	15-5	moraine	30	260	470	<15	3	78	<10	roads, fields, individual buildings
Godley lake	59 G	461555	5188206	3.4	13	43	>15	moraine	35	30	contact	<15	3	102	<10	roads, fields, individual buildings
Chholamo	45 R	672675	3099360	2.1	116	61	15-5	moraine	15	400	470	<15	3	41	<10	roads, fields, individual buildings
Lake 0071	45 R	676212	3084379	2.1	116	61	15-5	moraine	20	290	340	<15	7	1.71	10-1000	densely populated area
Hanpi k'ocha	18 L	743739	8534059	2.5	74	12	15-5	moraine	>45	contact	230	>25	7	1.9	>1000	densely populated area
Gopang Gath	43 S	708269	3601049	2.5	39	70	15-5	moraine	35	330	contact	15-25	6	27	10-1000	densely populated area
Spong Tongpo	43 S	658545	3769166	1.9	35	90	<5	moraine	30	190	contact	15-25	4	3.1	10-1000	densely populated area
Schako Tsho	45 R	658915	3095511	2	112	60	15-5	moraine	>45	65	contact	>25	6	18.14	10-1000	densely populated area
Imja Tsho	45 R	492610	3085944	4.9	121	57	<5	moraine	>45	230	contact	<15	6	65	>1000	densely populated area
Tsho Rolpa	45 R	448360	3082066	5.2	116	54	15-5	moraine	>45	contact	contact	>25	7	78	>1000	densely populated area
Thulagi Tsho	45 R	253755	3153985	4.2	101	44	<5	moraine	>45	contact	contact	<15	12	35	>1000	hydropower, buildings, roads
Dig Tsho	45 R	459210	3083375	5.2	117	55	<5	moraine	>45	contact	contact	>25	6	10.7	>1000	densely populated area
Lower Barung Tsho	45 R	509355	3074824	5	109	53	<5	moraine	>45	contact	contact	<15	7	83	>1000	hydropower, buildings, roads
Ludming Tsho	45 R	461884	3072885	5.2	112	52	<5	moraine	>45	contact	contact	15-25	3	50	10-1000	densely populated area
Chamlang South Tsho	45 R	495956	3069986	5.1	117	55	>15	moraine	>45	contact	contact	>25	7	32	10-1000	densely populated area
Chamlang North Tsho	45 R	495685	3073227	5.1	117	55	15-5	moraine	>45	contact	contact	>25	7	32	10-1000	densely populated area
<b>Selected GLOF events</b>		<b>Coordinates in UTM</b>		<b>TR.1</b>	<b>TR.2</b>	<b>TR.3</b>	<b>ME.1</b>	<b>ME.2</b>	<b>ME.3</b>	<b>ME.4</b>	<b>ME.5</b>	<b>ME.6</b>	<b>SR.1</b>	<b>SR.2</b>	<b>IM.1</b>	<b>IM.2</b>
Flatbreen lake - 2004	32 V	382775	6817696	0.7	32	5	15-5	moraine	35	400	contact	15-25	17	0.1	<10	roads, fields, individual buildings
Passu lake - 2007	43 S	489281	4034749	1.9	56	97	15-5	moraine	>45	50	contact	>25	6	1.8	>1000	densely populated area
Keara lake - 2009	19 L	481958	8377253	2.1	70	13	15-5	ice	25	contact	contact	>25	8	0.2	10-1000	densely populated area
513 lake - 2010	18 L	219809	8980678	3.6	73	7	15-5	moraine/bedrock	35	contact	contact	>25	8	4	10-1000	densely populated area
Halji lake - 2011	44 R	545635	3348799	5.8	77	57	15-5	ice	25	470	contact	>25	12	1	10-1000	historic temple, buildings, roads
Chorabari lake - 2013	44 R	314434	3403219	3.8	69	60	<5	moraine	30	contact	340	<15	17	0.4	>1000	historic temple, buildings, roads

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1070 **Table B.2 - Qualitative criteria evaluation for the global lake dataset. Low risk = 1, Medium risk = 2, High risk = 3.**

<b>Dangerous lakes - literature</b>	<b>Coordinates in UTM</b>		<b>TR.1</b>	<b>TR.2</b>	<b>TR.3</b>	<b>ME.1</b>	<b>ME.2</b>	<b>ME.3</b>	<b>ME.4</b>	<b>ME.5</b>	<b>ME.6</b>	<b>SR.1</b>	<b>SR.2</b>	<b>IM.1</b>	<b>IM.2</b>
Maud lake	59 G	459482 5185818	2	1	1	2	2	2	1	1	1	1	3	1	1
Godley lake	59 G	461555 5188206	2	1	1	1	2	2	2	3	1	1	3	1	1
Chholamo	45 R	672675 3099360	2	3	2	2	2	1	1	1	1	1	3	1	1
Lake 0071	45 R	676212 3084379	2	3	2	2	2	1	1	1	1	1	2	2	2
Hanpi k'ocha	18 L	743739 8534059	2	2	1	2	2	3	3	2	3	1	2	3	2
Gopang Gath	43 S	708269 3601049	2	1	2	2	2	2	2	3	2	1	3	2	2
Spong Tongpo	43 S	658545 3769166	2	1	2	3	2	2	2	3	2	1	2	2	2
Schako Tsho	45 R	658915 3095511	2	3	2	2	2	3	2	3	3	1	3	2	2
Imja Tsho	45 R	492610 3085944	3	3	2	3	2	3	2	3	1	1	3	3	2
Tsho Rolpa	45 R	448360 3082066	3	3	2	2	2	3	3	3	3	1	3	3	2
Thulagi Tsho	45 R	253755 3153985	3	3	1	3	2	3	3	3	1	3	3	3	3
Dig Tsho	45 R	459210 3083375	3	3	2	3	2	3	3	3	3	1	3	3	2
Lower Barung Tsho	45 R	509355 3074824	3	3	2	3	2	3	3	3	1	1	3	3	3
Ludming Tsho	45 R	461884 3072885	3	3	2	3	2	3	3	3	2	1	3	2	2
Chamlang South Tsho	45 R	495956 3069986	3	3	2	1	2	3	3	3	3	1	3	2	2
Chamlang North Tsho	45 R	495685 3073227	3	3	2	2	2	3	3	3	3	1	3	2	2
<b>Selected GLOF events</b>	<b>Coordinates in UTM</b>		<b>TR.1</b>	<b>TR.2</b>	<b>TR.3</b>	<b>ME.1</b>	<b>ME.2</b>	<b>ME.3</b>	<b>ME.4</b>	<b>ME.5</b>	<b>ME.6</b>	<b>SR.1</b>	<b>SR.2</b>	<b>IM.1</b>	<b>IM.2</b>
Flatbreen lake - 2004	32 V	382775 6817696	2	1	2	2	2	2	1	3	2	3	1	1	1
Passu lake - 2007	43 S	489281 4034749	2	2	2	2	2	3	2	3	3	1	2	3	2
Keara lake - 2009	19 L	481958 8377253	2	2	1	2	3	1	3	3	3	2	1	2	2
513 lake - 2010	18 L	219809 8980678	2	2	1	2	2	2	3	3	3	2	2	2	2
Halji lake - 2011	44 R	545635 3348799	3	2	2	2	3	1	1	3	3	3	2	2	3
Chorabari lake - 2013	44 R	314434 3403219	2	2	2	3	2	2	3	1	1	3	1	3	3

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**Table B.3 - Qualitative criteria evaluation for the Bolivian lake dataset. Low risk = 1, Medium risk = 2, High risk = 3.**

Lakes	Coordinates in UTM	TR.1	TR.2	TR.3	ME.1	ME.2	ME.3	ME.4	ME.5	ME.6	SR.1	SR.2	IM.1	IM.2
Apolobamba - Puina	19 L 476504 8384832	2	2	1	2	2	1	2	3	2	2	1	1	1
Apolobamba - Pelechuco	19 L 481205 8365591	2	2	1	2	2	3	3	2	2	2	2	3	2
Apolobamba - Hilo Hilo 1	19 L 492850 8354529	2	2	1	3	1	1	2	2	1	2	2	1	1
Apolobamba - Hilo Hilo 2	19 L 487996 8349572	2	2	1	3	1	1	1	2	2	2	1	1	1
Apolobamba - Hilo Hilo 3	19 L 487666 8349316	2	2	1	3	1	2	2	2	1	2	1	1	1
Apolobamba - Puyo Puyo	19 L 486275 8351196	2	2	1	2	1	1	1	3	2	1	1	1	1
Apolobamba - Taypi Cayuma 1	19 L 491182 8343142	2	2	1	2	1	2	2	2	1	1	1	1	1
Apolobamba - Taypi Cayuma 2	19 L 492072 8340807	2	2	1	3	2	3	1	1	1	1	1	1	1
Apolobamba - Cholina Cholina 1	19 L 497085 8337363	2	2	1	2	2	3	2	1	1	2	1	1	1
Apolobamba - Cholina Cholina 2	19 L 498284 8335884	2	2	1	3	2	1	1	1	3	1	1	1	1
Real - Laguna Glaciar	19 L 547085 8249728	2	2	1	3	1	2	2	3	2	2	2	3	2
Real - Cocoyo 1	19 L 556846 8251418	2	2	1	3	1	1	1	2	1	3	1	1	1
Real - Cocoyo 2	19 L 559120 8249880	2	2	1	2	1	1	1	2	1	3	1	1	1
Real - Cocoyo 3	19 L 560553 8247486	2	2	1	3	1	2	2	2	1	3	2	1	1
Real - Rinconada 1	19 L 552071 8244232	2	2	1	2	2	2	2	3	3	1	1	1	1
Real - Rinconada 2	19 L 550069 8242190	2	2	1	2	2	2	2	3	3	1	1	1	1
Real - Laguna Wara Warani	19 K 567694 8222503	2	2	1	2	1	2	2	2	1	1	2	1	1
Real - Umapalca	19 K 584186 8220965	2	2	1	3	1	2	3	2	1	2	2	1	1
Real - Condoriri	19 K 578927 8210860	2	2	1	2	1	1	1	1	2	1	2	1	1
Real - Comunidad Pantini	19 K 612872 8182149	2	2	1	3	1	2	2	1	1	1	1	1	1
Mururata - Laguna Arkhata	19 K 624521 8172040	2	2	1	2	1	3	2	3	2	3	3	3	2
Tres Cruces - North	19 K 670245 8126070	2	2	1	3	2	2	1	2	1	1	1	1	1
Tres Cruces - Mining camp west	19 K 674446 8120893	2	2	1	2	1	2	2	1	1	3	1	2	3
Tres Cruces - Mining camp east	19 K 678278 8121207	2	2	1	3	2	1	1	1	1	2	1	2	3
Tres Cruces - Laguna Huallatani	19 K 675910 8118767	2	2	1	2	1	1	1	1	1	2	3	3	2

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