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

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Abstract

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

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; Anacona 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

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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):

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

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

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

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

6

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

226

227

TRIGGERS (TR)

TR.1 regional seismic activity
TR.2 intense precipitation events
TR.3 high temperature events

MECHANISMS (ME)

ME.1 dam freeboard
ME.2 dam type

rockfall/landslide susceptibility
icefall/snow avalanche susceptibility
calving susceptibility

ME.3 steepest slope surrounding lake
ME.4 distance between lake and steepest slope
ME.5 distance between lake and glacier
ME.6 parent glacier snout steepness

GLOF INITIATION

dam overtopping
dam collapse

FLOOD WAVE SIZE/RUNOUT (SR)

SR.1 travel distance of GLOF
SR.2 lake volume

IMPACT (IM)

IM.1 potential loss of human life
IM.2 potential loss of infrastructure
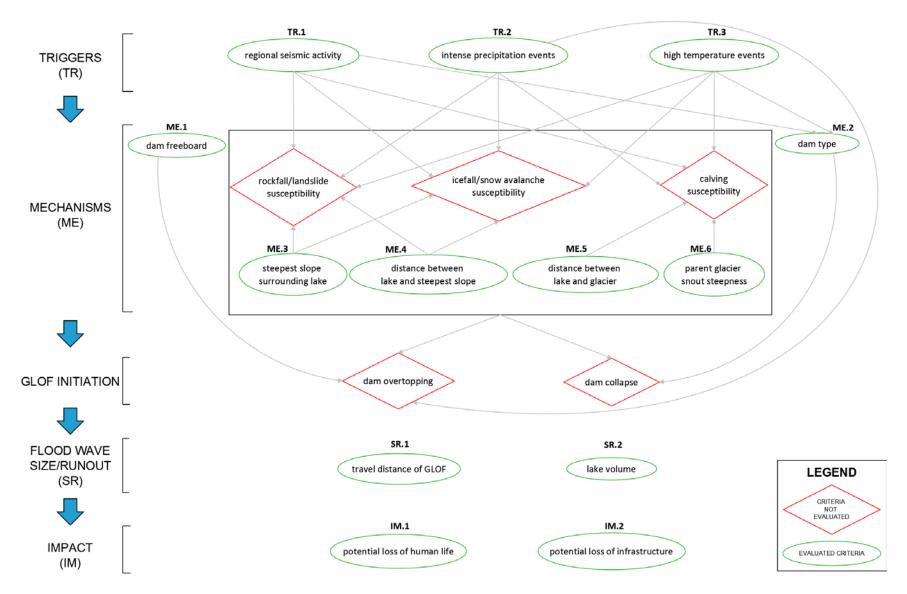
LEGEND

CRITERIA NOT EVALUATED

EVALUATED CRITERIA

228

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

229

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

accepted/rejected criterion	reason	indication
	dam, region or scenario specific	A
	field assessment required	B
rejected criterion	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

9

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	piping/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	piping 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

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

Following the identification of appropriate selection criteria from the Description Problem stage, all lakes within a region can be judged according to those criteria in order to determine which lakes, if any, represent a GLOF risk to downstream communities. This can be achieved remotely (i.e. without the need for fieldwork), and without cost, as we demonstrate below. Our approach can be applied to a single lake or to a complete lake inventory within a region. It would be particularly useful in identifying sites for further detailed field studies, outburst flood modelling, or monitoring. In this study, we apply our method on a number of lakes that had been identified in previous studies as representing a threat to downstream communities. Fig. 2 illustrates the steps that need to be followed for the method to be applied in a chosen region. For the trigger criteria (TR.1, 2, 3), the user will need to open the indicated databases (Global seismic hazard map, BIOCLIM variables 4 and 5) in a GIS in order to evaluate the lakes. For all other criteria, Google Earth Pro is sufficient for evaluation. 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 <0.01km² (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 - Kropácek 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 where 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
Triggers								
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
Mechanisms								
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	
Flood wave size/runout								
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	m3 * 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)
Impact								
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	<10 agricultural fields, roads etc.	houses, bridges etc.	hydropower, mining camp etc.	Google Earth/Bing Maps/web info	qualitative	

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2.3.4 Sensitivity analysis

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

2.3.4.1 Lambda cutting level

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

2.3.4.2 Criteria thresholds

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

3. Results

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

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

Table 3 – Potentially dangerous lakes and selected GLOF events derived from previous studies. Risk level derived from the MCDA method. Decimal percentages (i.e. from 0.5 to 1) indicate the level of confidence that a lake belongs to the specific 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; Vilímek et al., 2015	18 L	219809	8980678	0.65
Halji lake - 2011	Nepal	Kropácek et al., 2015	44 R	545635	3348799	0.79
Chorabari lake - 2013	India	Das et al., 2015	44 R	314434	3403219	0.59

3.2 Lambda cutting level sensitivity analysis

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

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

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

Dangerous lakes - literature	λ-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	**λ-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
Chorabari Lake - 2013	0.59	0.73	0.85	0.93	0.98

3.3 Criteria thresholds sensitivity analysis

The results of this second sensitivity analysis are shown in Table 5. Respectively, Rows A and B indicate the number of lakes that change risk class and change risk classification confidence level when each criterion threshold is modified. Several criteria lead to little or no change to the number of lakes that are re-classified when their thresholds are modified, and only minor changes in the percentage of confidence in each risk class. These are intense precipitation events (TR.2), distance between lake and 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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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 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 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	0.58	0.65	0.58	0.58	1	0
Hanpi k'ocha	0.62	0.58	0.62	0.62	0.62	0.62	0.62	0.62	0.58	0.62	2	0
Gopang Gath	0.92	0.81	0.92	0.92	0.92	0.92	0.92	0.95	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	0.77	0.54	0.77	0.77	0.77	0.57	0.77	0	2
Passu Lake - 2007	0.65	0.58	0.65	0.58	0.65	0.65	0.65	0.65	0.58	0.65	3	0
Keara Lake - 2009	0.52	0.58	0.52	0.52	0.52	0.52	0.52	0.59	0.61	0.52	2	1
513 Lake - 2010	0.65	0.58	0.65	0.65	0.58	0.65	0.65	0.59	0.58	0.58	5	0
Halji Lake - 2011	0.79	0.79	0.92	0.79	0.79	0.79	0.79	0.79	0.91	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

		TR.1	TR.2	TR.3	ME.3	ME.4	ME.5	SR.1	SR.2	IM.1		
A		4	0	1	1	0	0	3	3	1		
B		8	1	3	4	1	0	1	4	2		

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

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

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

Table 6 – Risk levels for potentially dangerous lakes in the Bolivian Andes as identified by Cook et al. (2016). Decimal percentages indicate the level of confidence that a lake belongs to the specific risk class (Low risk = Green, Medium risk = 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 - Umapalca	19 K	584186	8220965	0.58
Real - Condoriri	19 K	578927	8210860	0.98
Real - Comunidad Pantini	19 K	612872	8182149	0.97
Mururata - 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 Cruzes - Mining camp east	19 K	678278	8121207	0.77
Tres Cruces - Laguna Huallatani	19 K	675910	8118767	0.77

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

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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

4.4 MCDA model sensitivity

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

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

One of the key benefits of the MCDA approach is the use of the Description Problem approach to decide upon appropriate GLOF risk assessment criteria. However, the choice of thresholds for each criterion remains uncertain in some cases (see also Supplementary Data - Appendix A). Hence, we also explored the effect of changing the threshold values for the high-risk category of each criterion (Table 5). For the most part, Table 5 illustrates that alteration of the thresholds for most criteria yields relatively few changes in risk categorization for each lake in our sample. This is due in large part to the fact that many of the lakes in our sample already fall into the high-risk category for each criterion, meaning that a relaxation of the criteria for high risk has little effect on the results. Nevertheless, there are a few notable exceptions. By relaxing the seismic activity (TR.1) high-risk threshold, 4 lakes are re-graded as high risk. However, this probably constitutes an unrealistic reclassification whereby mountain ranges with modest or low seismic activity are ascribed a higher risk rating. Risk managers 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 (0.1×10^6 m^3) to very large lakes (770×10^6 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 1×10^6 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

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

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

Our MCDA approach, through the construction of a Description Problem (section 2.2), streamlines the wide array of criteria that have been used previously to assess GLOF risk. Nonetheless, since our approach offers a rapid, first pass assessment of GLOF risk, the final 13 criteria used inevitably ignore some criteria that cannot be assessed remotely (e.g. vulnerability factors, specific details about the nature of the dam, etc.). Hence, there remain situations where it would be advantageous to use existing GLOF risk assessments that have been tailored to specific lakes, regions or contexts, or where 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 'λ-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 PGAmax (m s^{-2}) 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^2) and high (>0.5 m/s^2) 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^2 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 (0.1×10^6 m^3) to very large lakes (770×10^6 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: $<1 \times 10^6$ m^3 (low risk), 1×10^6 m^3 - 10×10^6 m^3 (medium risk) and 10 x

1036 10^6 m^3 - 100×10^6 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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Appendix B - Criteria values for lake evaluation

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

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	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
Selected GLOF events	**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
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

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 Cruzes - 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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