Kougkoulos, I, Cook, SJ, Jomelli, V, Clarke, L, Symeonakis, E, Dortch, JM, Edwards, LA and Merad, M

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

http://researchonline.ljmu.ac.uk/id/eprint/9385/

Article

Citation (please note it is advisable to refer to the publisher's version if you intend to cite from this work)

Kougkoulos, I, Cook, SJ, Jomelli, V, Clarke, L, Symeonakis, E, Dortch, JM, Edwards, LA and Merad, M (2017) Use of multi-criteria decision analysis to identify potentially dangerous glacial lakes. Science of the Total Environment, 621. pp. 1453-1466. ISSN 0048-9697

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

Ioannis Kougkoulos[1], Simon J. Cook[2], Vincent Jomelli[3], Leon Clarke[1], Elias Symeonakis[1], Jason M. Dortch[4], Laura A. Edwards[5], and Myriam Merad[6,7]

[1]School of Science and the Environment, Manchester Metropolitan University, Chester Street, Manchester, M1 5GD, UK

[2]Geography, School of Social Sciences, University of Dundee, Nethergate, Dundee DD1 4HN, UK

[3]Université Paris 1 Panthéon-Sorbonne, CNRS-LGP, 92195 Meudon, France

[4]Department of Geography, University of Manchester, Oxford Road, Manchester, M13 9PL, UK

[5]School of Natural Sciences and Psychology, Liverpool John Moores University, Liverpool, L3 3AF, UK

[6]Université Paris-Dauphine, LAMSADE-CNRS, 75775 Paris Cedex 16, France

[7]Université de Nice, ESPACE-CNRS, F-06204 Nice Cedex 03, France

Correspondence to: Ioannis Kougkoulos (i.kougkoulos@mmu.ac.uk, ioannis.kougkoulos@gmail.com) or Simon Cook (s.y.cook@dundee.ac.uk)

Keywords: Glacier shrinkage, Glacial lake outburst flood (GLOF), Geohazards, Risk assessment, Decision theory, Multi-criteria decision analysis (MCDA)

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

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

1. Introduction

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

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

Nonetheless, some hazard and risk assessments, although developed initially for, and applied to, specific regions, have been designed in such a way that they can be applied elsewhere. Most are designed for moraine-dammed lakes. Notable examples include those of McKillop and Clague (2007b), Mergili and Schneider (2011), and Rounce et al. (2016). McKillop and Clague (2007b) developed an objective method for assessing outburst flood hazard from moraine-dammed lakes in British Columbia, which uses remote sensing methods. Nevertheless, as a hazard assessment it does not evaluate impacts, exposure, vulnerability or risk, and cannot be applied to bedrock- or ice-dammed lakes, which may also exist within the same region. Mergili and Schneider (2011) developed a GLOF hazard assessment based on remote sensing data that could be applied to any lake type, but their method does not consider impacts on humans or infrastructure. Rounce et al. (2016) presented an objective and repeatable method for GLOF hazard and impact assessment, but this was based on moraine-dammed lakes only.

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

Our objectives are: (1) to define a set of robust (i.e. exhaustive, non-redundant, consistent) susceptibility and potential downstream impact criteria that will be used to define GLOF risk; (2) to use these criteria to assess GLOF risk for 22 lakes around the world and compare our results with those of previous GLOF risk and hazard studies; (3) to undertake sensitivity testing of the MCDA model in order to evaluate the robustness of the method; and (4) apply our model to assess the risk posed by 25 lakes in the Bolivian Andes, which represents a case study of how our model could be used.

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

2. Methodology

2.1 Background to setting an MCDA problem

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

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

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

Next, these criteria will be used to frame a Sorting Problem whereby lakes will be classed according to high, medium or low risk, which can be used to narrow future research or mitigation focus onto the most dangerous lakes. The Sorting Problem has been chosen in this study instead of ranking or choice problems because it offers the possibility of evaluating a large set of lakes, but also a single lake. The Ranking Problem suffers from the shortcoming that at least two lakes need to be studied in order for the assessment to take place; the Choice Problem will only define the highest risk lake. Our MCDA approach for GLOF risk is designed to be intuitive, to use freely available datasets, and be applicable to any glacial lake irrespective of dam type or region of the world.

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

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

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

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

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

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

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

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

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

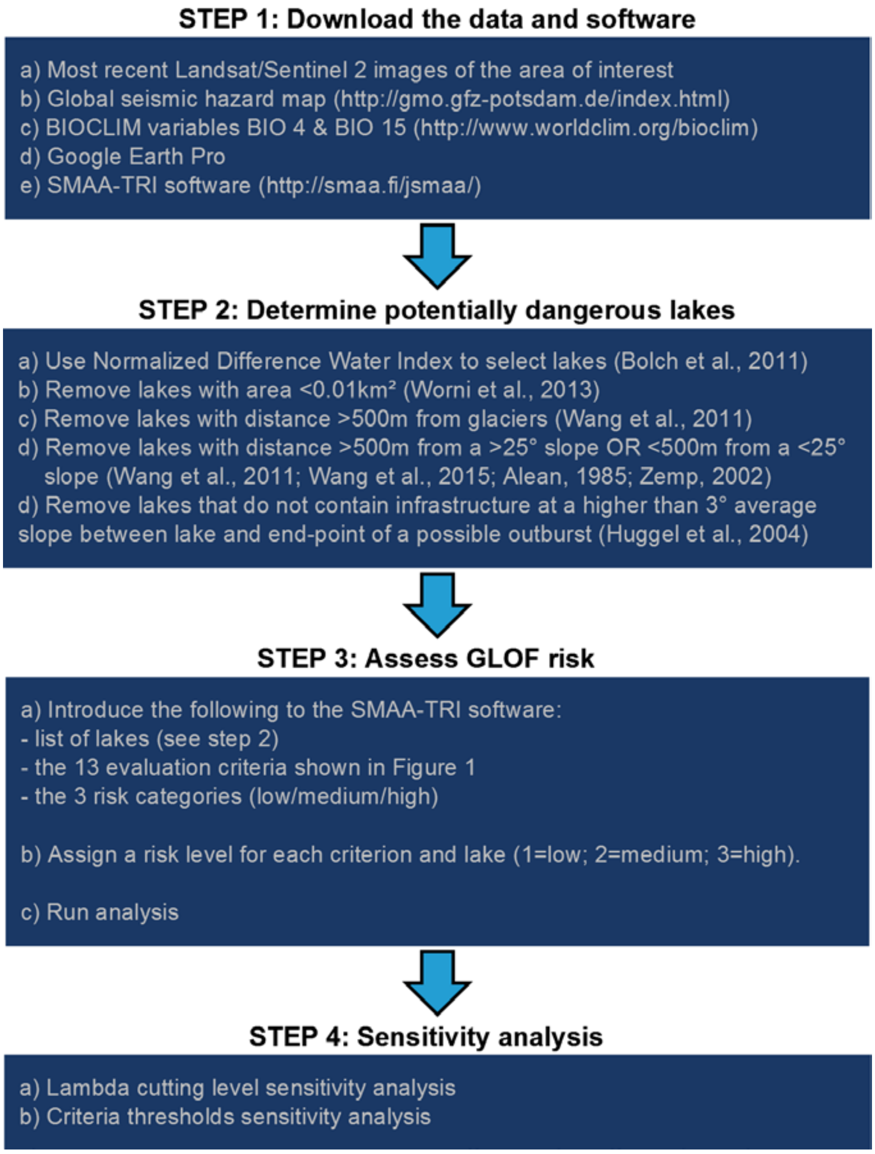
18	lake area and/or size	4,10,14,19,24,26	D (with SR.2)
19	breach volume	6	B
20	lake area change	11,14,15,28	D (with SR.2)
21	lake depth	4,21,26	D (with SR.2)
22	distant flank steepness of the dam	1,4,13,15,16	A,B
23	width and/or height ratio of dam	3,4,8,10,12,13	B
24	top width of dam	13,19	A, B
25	steepness of moraine	2	A
26	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).

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

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

2.3.1 Choice of lakes for testing

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

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

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

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

2.3.2 SMAA-TRI software

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

2.3.3 Setting risk thresholds and codes for evaluating individual criteria

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

The relative importance of each criterion can differ, and there are numerous methods for determining the relative weights of individual criteria (Saaty, 1977; Chen et al., 2001; Figueira and Roy, 2002). In a natural hazard context, weights are typically determined subjectively by the hazard/risk experts or based on statistical methods (such as regression and principal component analysis) (Chen et al., 2001). However, since there is insufficient empirical evidence by which to determine the relative importance of each criterion in GLOF risk or hazard assessments, the decision was made here not to assign any weights. Nonetheless, this could be undertaken in future studies if understanding of GLOF controlling factors were to develop sufficiently.

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	agricultural fields, roads etc.	houses, bridges etc.	hydropower, mining camp etc.	Google Earth/Bing Maps/web info	qualitative	

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

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

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
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

4. Discussion

4.1 Comparisons with existing GLOF hazard and risk assessments

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

4.2 Comparisons of model results with GLOF-generating lakes

Table 3 also presents pre-GLOF risk assessments for seven lakes that have already generated GLOFs. This selection of GLOF-generating lakes comprises a mixture of ice, moraine and bedrock dams located in different regions around the world. Flatbreen lake burst in 2004 and generated a debris flow that reached the valley bottom ~1000m below the lake (Breien et al., 2008). This lake is graded as low risk (a result that is sustained throughout the sensitivity analyses – Tables 4 and 5) due to both downstream impact parameters (IM.1 and IM.2) falling into the low impact category - there is no significant population or infrastructure in the immediate floodpath downstream (except farmland and a minor road). The Passu lake, Keara lake and lake 513 GLOF events are known to have damaged roads or bridges, or to have increased downstream sedimentation causing malfunction of water-treatment plants or damage to agricultural land (Ashraf et al., 2012; Carey et al., 2012; Hoffmann and Wegenmann, 2013; Klimeš et al., 2014; Vilímek et al., 2015). Nevertheless, they did not cause any casualties or fatalities. These factors are key drivers of the medium-risk classification from our MCDA method (Table 3). In contrast, Halji and Chorabari lakes are situated in relatively close proximity to downstream infrastructure and relatively high population numbers meaning that the overall risk was graded as high.

4.3 Potentially dangerous glacial lakes of the Bolivian Andes

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

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

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

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

4.5 The use of MCDA in GLOF risk assessments

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

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

5. Conclusion

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

We assessed the risk of 16 potentially dangerous glacial lakes as well as 6 lakes that have already generated GLOFs in the past (between 2004 and 2013). Our results for the 16 extant lakes compare favourably with previous risk and hazard assessments, which have generally focused on specific regions or glacial lake contexts. This indicates that our MCDA model can be applied in a range of contexts globally. Further, we undertook sensitivity analyses of our model to explore the robustness of results and model assumptions. To our knowledge, this is the first time sensitivity analysis has been performed for a GLOF risk or hazard assessment model. Two sensitivity analyses were undertaken. In the first, the proportion of criteria that need to be graded as ‘high risk’ in order to grade the overall risk as ‘high’ was relaxed (the so-called ’λ-cutting level’). This identified several lakes that remain within the same risk class as this cutting level is increased, which gives confidence to the user in making risk management decisions about those lakes. The second sensitivity test involved relaxing the threshold for ‘high risk’ for each criterion. This generally revealed that the original risk thresholds used here were robust, although some lakes were identified that might warrant further study because they changed readily to a higher risk class. We applied the tested method on 25 glacial lakes in the data-scarce Bolivian Andes, and found that 22 of these lakes represent low risk, and therefore do not currently require further attention. Nevertheless, further detailed investigation or action is required for two lakes rated as medium risk (Pelechuco, Laguna Glaciar), and one lake rated as high risk (Laguna Arkhata).

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

Acknowledgments Ioannis Kougkoulos is funded through an Environmental Science Research Centre PhD studentship at Manchester Metropolitan University. We thank Marc Lassagne, Associate Professor from Arts et Métiers ParisTech, for providing valuable insights and suggestions for this article. We thank Adam Emmer and three anonymous reviewers for their helpful and insightful reviews of our manuscript.

References

Aggarwal, A., Jain, S.K., Lohani, A.K., Jain, N., 2016. Glacial lake outburst flood risk assessment using combined approaches of remote sensing, GIS and dam break modelling. Geomatics, Nat. Hazards Risk 7, 18–36. doi:10.1080/19475705.2013.862573

Aggarwal, S., Rai, S.C., Thakur, P.K., Emmer, A., 2017. Inventory and recently increasing (GLOF) susceptibility of glacial lakes in Sikkim, Eastern Himalaya. Geomorphology. doi:https://doi.org/10.1016/j.geomorph.2017.06.014

Akgun, A., Türk, N., 2010. Landslide susceptibility mapping for Ayvalik (Western Turkey) and its vicinity by multicriteria decision analysis. Environ. Earth Sci. 61, 595–611. doi:10.1007/s12665-009-0373-1

Alean J., 1985. Ice avalanches: some empirical information about their formation and reach. J Glaciol. 31(109), 324–33.

Allen, S.K., Schneider, D., Owens, I.F., 2009. First approaches towards modelling glacial hazards in the Mount Cook region of New Zealand's Southern Alps. Nat. Hazards Earth Syst. Sci. 9, 481–499. doi:10.5194/nhess-9-481-2009

Allen, S.K., Rastner, P., Arora, M., Huggel, C., Stoffel, M., 2015. Lake outburst and debris flow disaster at Kedarnath, June 2013: hydrometeorological triggering and topographic predisposition. Landslides 1–13.

Allen, S.K., Linsbauer, A., Randhawa, S.S., Huggel, C., Rana, P., Kumari, A., 2016. Glacial lake outburst flood risk in Himachal Pradesh, India: an integrative and anticipatory approach considering current and future threats. Nat. Hazards 1–23. doi:10.1007/s11069-016-2511-x

Anacona, P.I., Mackintosh, A., Norton, K., 2015. Reconstruction of a glacial lake outburst flood (GLOF) in the Engaño Valley, Chilean Patagonia: Lessons for GLOF risk management. Sci. Total Environ. 527–528, 1–11. doi:10.1016/j.scitotenv.2015.04.096

Ashraf, A., Naz, R., Roohi, R., 2012. Glacial lake outburst flood hazards in Hindukush, Karakoram and Himalayan Ranges of Pakistan: implications and risk analysis. Geomatics, Nat. Hazards Risk 3, 113–132. doi:10.1080/19475705.2011.615344

Behzadian, M., Kazemzadeh, R.B., Albadvi, A., Aghdasi, M., 2010. PROMETHEE: A comprehensive literature review on methodologies and applications. Eur. J. Oper. Res. 200, 198–215. doi:10.1016/j.ejor.2009.01.021

Benn, D.I., Wiseman, S., Hands, K.A., 2001. Growth and drainage of supraglacial lakes on debris-mantled Ngozumpa Glacier, Khumbu Himal, Nepal. J. Glaciol. 47, 626–638. doi:10.3189/172756501781831729

Bolch, T., Buchroithner, M.F., Peters, J., Baessler, M., Bajracharya, S., 2008. Identification of glacier motion and potentially dangerous glacial lakes in the Mt. Everest region/Nepal using spaceborne imagery. Nat. Hazards Earth Syst. Sci. 8, 1329–1340. doi:10.5194/nhess-8-1329-2008

Bolch, T., Peters, J., Yegorov, A., Pradhan, B., Buchroithner, M., Blagoveshchensky, V., 2011. Identification of potentially dangerous glacial lakes in the northern Tian Shan. Nat. Hazards 59, 1691–1714. doi:10.1007/978-3-642-25495-6_12

Breien, H., De Blasio, F. V., Elverhøi, A., Høeg, K., 2008. Erosion and morphology of a debris flow caused by a glacial lake outburst flood, Western Norway. Landslides 5, 271–280. doi:10.1007/s10346-008-0118-3

Brito, A.J., de Almeida, A.T., Mota, C.M.M., 2010. A multicriteria model for risk sorting of natural gas pipelines based on ELECTRE TRI integrating Utility Theory. Eur. J. Oper. Res. 200, 812–821. doi:10.1016/j.ejor.2009.01.016

Brito, M.M. De, Evers, M., 2016. Multi-criteria decision-making for flood risk management: a survey of the current state of the art 1019–1033. doi:10.5194/nhess-16-1019-2016

Carey, M., Huggel, C., Bury, J., Portocarrero, C., Haeberli, W., 2012. An integrated socio-environmental framework for glacier hazard management and climate change adaptation: Lessons from Lake 513, Cordillera Blanca, Peru. Clim. Change 112, 733–767. doi:10.1007/s10584-011-0249-8

Carrivick, J.L., Tweed, F.S., 2013. Proglacial Lakes: Character, behaviour and geological importance. Quat. Sci. Rev. 78, 34–52. doi:10.1016/j.quascirev.2013.07.028

Carrivick, J.L., Tweed, F.S., 2016. A global assessment of the societal impacts of glacier outburst floods. Glob. Planet. Change 144, 1–16. doi:10.1016/j.gloplacha.2016.07.001

Chen, K., Blong, R., Jacobson, C., 2001. MCE-RISK: Integrating multicriteria evaluation and GIS for risk decision-making in natural hazards. Environ. Model. Softw. 16, 387–397. doi:10.1016/S1364-8152(01)00006-8

Clague, J.J., Evans, S.G., 2000. A review of catastrophic drainage of moraine-dammed lakes in British Columbia . Quaternary Science Reviews A review of catastrophic drainage of moraine-dammed lakes in British Columbia. Quat. Sci. Rev. 19, 1763–1783. doi:10.1016/S0277-3791(00)00090-1

Cook, S.J., Quincey, D.J., 2015. Estimating the volume of Alpine glacial lakes. Earth Surf. Dyn. 3, 559–575. doi:10.5194/esurf-3-559-2015

Cook, S.J., Kougkoulos, I., Edwards, L.A., Dortch, J., Hoffmann, D., 2016. Glacier change and glacial lake outburst flood risk in the Bolivian Andes. Cryosph. 10, 2399–2413. doi:10.5194/tc-10-2399-2016

Costa and Schuster (1988): The formation and failure of natural dams. Geological Society of America Bulletin 100, 1054-1068.

Damart, S., Dias, L.C., Mousseau, V., 2007. Supporting groups in sorting decisions: Methodology and use of a multi-criteria aggregation/disaggregation DSS. Decis. Support Syst. 43, 1464–1475. doi:10.1016/j.dss.2006.06.002

Das, S., Kar, N.S., Bandyopadhyay, S., 2015. Glacial lake outburst flood at Kedarnath, Indian Himalaya: a study using digital elevation models and satellite images. Nat. Hazards 77, 769–786. doi:10.1007/s11069-015-1629-6

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

Emmer, A., Vilímek, V., 2013. Review Article: Lake and breach hazard assessment for moraine-dammed lakes: an example from the Cordillera Blanca (Peru). Nat. Hazards Earth Syst. Sci. 13, 1551–1565. doi:10.5194/nhess-13-1551-2013

Emmer, A., Vilímek, V., 2014. New method for assessing the susceptibility of glacial lakes to outburst floods in the Cordillera Blanca, Peru. Hydrol. Earth Syst. Sci. 18, 3461–3479. doi:10.5194/hess-18-3461-2014

Emmer, A., Klimeš, J., Mergili, M., Vilímek, V., Cochachin, A., 2016a. 882 lakes of the Cordillera Blanca: An inventory, classification, evolution and assessment of susceptibility to outburst floods. Catena 147, 269–279. doi:10.1016/j.catena.2016.07.032

Emmer, A., Vilímek, V., Huggel, C., Klimeš, J., Schaub, Y., 2016b. Limits and challenges to compiling and developing a database of glacial lake outburst floods. Landslides 1–6. doi:10.1007/s10346-016-0686-6Figueira, J., Greco, S., Roy, B., Słowiński, R., 2013. An Overview of ELECTRE Methods and their Recent Extensions. J. Multi-Criteria Decis. Anal. 20, 61–85. doi:10.1002/mcda.1482

Figueira, J., Roy, B., 2002. Determining the weights of criteria in the ELECTRE type methods with a revised Simos' procedure. Eur. J. Oper. Res. 139, 317–326. doi:10.1016/S0377-2217(01)00370-8

Frey, H., Huggel, C., Bühler, Y., Buis, D., Burga, M.D., Choquevilca, W., Fernandez, F., García Hernández, J., Giráldez, C., Loarte, E., Masias, P., Portocarrero, C., Vicuña, L., Walser, M., 2016. A robust debris-flow and GLOF risk management strategy for a data-scarce catchment in Santa Teresa, Peru. Landslides. doi:10.1007/s10346-015-0669-z

Frey, H., Huggel, C., Paul, F., Haeberli, W., 2010. Automated detection of glacier lakes based on remote sensing in view of assessing associated hazard potentials. Proc. 10th Int. sympsoium high Mt. Remote sending Cartogr. 23–30.

Fujita, K., Suzuki, R., Nuimura, T., Sakai, A., 2008. Performance of ASTER and SRTM DEMs, and their potential for assessing glacial lakes in the Lunana region, Bhutan Himalaya. J. Glaciol. 54, 220–228. doi:10.3189/002214308784886162

Grabs, W.E., Hanisch, J., 1992. Objectives and Prevention Methods for Glacier Lake Outburst Moods (GLOFs). Snow Glacier Hydrol. 218, 341–352.

Haeberli, W., 1983. Frequency and characteristics of glacier floods in the Swiss Alps, Ann. Glaciol., 4, 85–90.

Haemmig, C., Huss, M., Keusen, H., Hess, J., Wegmüller, U., Ao, Z., Kulubayi, W., 2014. Hazard assessment of glacial lake outburst floods from Kyagar glacier, Karakoram mountains, China. Ann. Glaciol. 55, 34–44. doi:10.3189/2014AoG66A001

Hegglin, E., Huggel, C., 2008. An Integrated Assessment of Vulnerability to Glacial Hazards. Mt. Res. Dev. 28, 299–309. doi:10.1659/mrd.0976

Hoffmann, D., Weggenmann, D., 2013. Climate Change Induced Glacier Retreat and Risk Management: Glacial Lake Outburst Floods (GLOFs) in the Apolobamba Mountain Range, Bolivia. Chang. Disaster Risk Manag. 71–87. doi:10.1007/978-3-642-31110-9_5

Huang, I.B., Keisler, J., Linkov, I., 2011. Multi-criteria decision analysis in environmental sciences: Ten years of applications and trends. Sci. Total Environ. 409, 3578–3594. doi:10.1016/j.scitotenv.2011.06.022

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

Huggel, C., Kääb, A., Haeberli, W., Teysseire, P., Paul, F., 2002. Remote sensing based assessment of hazards from glacier lake outbursts: a case study in the Swiss Alps. Can. Geotech. J. 39, 316–330. doi:10.1139/t01-099

ICIMOD. 2011. Glacial lakes and glacial lake outburst floods in Nepal. International Centre for Integrated Mountain Development (ICIMOD): Kathmandu.

IPCC, 2014: Summary for Policymakers. Working Group II Contribution to the IPCC Fifth Assessment Report Climate Change 2014: Impacts, Adaptation and Vulnerability. Cambridge University Press, Cambridge, UK.

Ishizaka, A., Pearman, C., Nemery, P., 2012. AHPSort: an AHP-based method for sorting problems. Int. J. Prod. Res. 50, 4767–4784. doi:10.1080/00207543.2012.657966

ISO 31000:2009 (2009) Risk management - Principles and guidelines. International Organization for Standardization, Geneva, Switzerland.

Ives JD, Shrestha RB, Mool PK. 2010. Formation of glacial lakes in the Hindu Kush-Himalayas and GLOF risk assessment. ICIMOD: Kathmandu.

Janský, B., Šobr, M., Engel, Z., 2010. Outburst flood hazard: Case studies from the Tien-Shan Mountains, Kyrgyzstan. Limnologica 40, 358–364. doi:10.1016/j.limno.2009.11.013

Khanal, N.R., Mool, P.K., Shrestha, A.B., Rasul, G., Ghimire, P.K., Shrestha, R.B., Joshi, S.P., 2015. A comprehensive approach and methods for glacial lake outburst flood risk assessment, with examples from Nepal and the transboundary area. Int. J. Water Resour. Dev. 31, 219–237. doi:10.1080/07900627.2014.994116

Klimeš, J., Benešová, M., Vilímek, V., Bouška, P., Cochachin Rapre, A., 2014. The reconstruction of a glacial lake outburst flood using HEC-RAS and its significance for future hazard assessments: an example from Lake 513 in the Cordillera Blanca, Peru. Nat. Hazards 71, 1617–1638. doi:10.1007/s11069-013-0968-4

Kropáček, J., Neckel, N., Tyrna, B., Holzer, N., Hovden, A., Gourmelen, N., Schneider, C., Buchroithner, M., Hochschild, V., 2015. Repeated glacial lake outburst flood threatening the oldest Buddhist monastery in north-western Nepal. Nat. Hazards Earth Syst. Sci. 15, 2425–2437. doi:10.5194/nhess-15-2425-2015

Lin, W.T., 2008. Earthquake-induced landslide hazard monitoring and assessment using SOM and PROMETHEE techniques: A case study at the Chiufenershan area in Central Taiwan. Int. J. Geogr. Inf. Sci. 22, 995–1012. doi:10.1080/13658810801914458

Malczewski, J., Rinner, C., 2015. Multicriteria Decision Analysis in Geographic Information Science, Analysis methods. doi:10.1007/978-3-540-74757-4

Marinoni, O., 2005. A stochastic spatial decision support system based on PROMETHEE. Int. J. Geogr. Inf. Sci. 19, 51–68. doi:10.1080/13658810412331280176

McKillop, R.J., Clague, J.J., 2007a. Statistical, remote sensing-based approach for estimating the probability of catastrophic drainage from moraine-dammed lakes in southwestern British Columbia. Glob. Planet. Change 56, 153–171. doi:10.1016/j.gloplacha.2006.07.004

McKillop, R.J., Clague, J.J., 2007b. A procedure for making objective preliminary assessments of outburst flood hazard from moraine-dammed lakes in southwestern British Columbia. Nat. Hazards 41, 131–157. doi:10.1007/s11069-006-9028-7

Merad, M.M., Verdel, T., Roy, B., Kouniali, S., 2004. Use of multi-criteria decision-aids for risk zoning and management of large area subjected to mining-induced hazards. Tunn. Undergr. Sp. Technol. 19, 125–138. doi:10.1016/S0886-7798(03)00106-8

Mergili, M., Schneider, J.F., 2011. Regional-scale analysis of lake outburst hazards in the southwestern Pamir , Tajikistan , based on remote sensing and GIS 1447–1462. doi:10.5194/nhess-11-1447-2011

Mertes, J.R., Thompson, S.S., Booth, A.D., Gulley, J.D., Benn, D.I., 2016. A conceptual model of supra-glacial lake formation on debris-covered glaciers based on GPR facies analysis. Earth Surf. Process. Landforms. doi:10.1002/esp.4068

Mousseau, V., Slowinski, R., Zielniewicz, P., 2000. A user-oriented implementation of the ELECTRE-TRI method integrating preference elicitation support. Comput. Oper. Res. 27, 757–777. doi:10.1016/S0305-0548(99)00117-3

Nemery, P., Lamboray, C., 2008. Flow sort: A flow-based sorting method with limiting or central profiles. Top 16, 90–113. doi:10.1007/s11750-007-0036-x

O'Connor, J.E., Hardison III, J.H., Costa, J.E., 2001. Debris Flows from Failures of Neoglacial- Age Moraine Dams in the Three Sisters and Mount Jefferson Wilderness Areas, Oregon, USGS Professional Paper.

Omelicheva, M.Y., 2011. Natural Disasters: Triggers of Political Instability? Int. Interact. 37, 441–465. doi:10.1080/03050629.2011.622653

Petrov, M.A., Sabitov, T.Y., Tomashevskaya, I.G., Glazirin, G.E., Chernomorets, S.S., Savernyuk, E.A., Tutubalina, O. V., Petrakov, D.A., Sokolov, L.S., Dokukin, M.D., Mountrakis, G., Ruiz-Villanueva, V., Stoffel, M., 2017. Glacial lake inventory and lake outburst potential in Uzbekistan. Sci. Total Environ. 592, 228–242. doi:10.1016/j.scitotenv.2017.03.068

Reynolds, J.M., 2003. Development of glacial hazard and risk minimisation protocols in rural environments Methods of glacial hazard assessment and management in the Cordillera Blanca , Peru April 2003 Project No : R7816 . H.

Richardson, S.D., Reynolds, J.M., 2000. An overview of glacial hazards in the Himalayas. Quat. Int. 65–66, 31–47. doi:10.1016/S1040-6182(99)00035-X

Rickenmann, D., 1999. Empirical relationships for debris flows. Nat. Hazards 19, 47–77.

Rickenmann D., 2005. Runout prediction methods. Jakob M, Hungr O, editors. Debris-flow hazards and related phenomena. Berlin/Heidelberg: Springer. p. 305–24.

Rounce, D.R., McKinney, D.C., Lala, J.M., Byers, A.C., Watson, C.S., 2016. A New Remote Hazard and Risk Assessment Framework for Glacial Lakes in the Nepal Himalaya. Hydrol. Earth Syst. Sci. Discuss. 1–48. doi:10.5194/hess-2016-161

Rounce, D.R., Byers, A.C., Byers, E.A., McKinney, D.C., 2017. Brief communication: Observations of a glacier outburst flood from Lhotse Glacier, Everest area, Nepal. Cryosphere 11, 443–449. doi:10.5194/tc-11-443-2017a

Rounce, D. R., Watson, C. S., McKinney, D. C., Identification of hazard and risk for glacial lakes in the Nepal Himalaya using satellite imagery from 2000 - 2015, Remote Sens. 9, 654; doi:10.3390/rs9070654, 2017b

Roy, B., 1993. Decision science or decision aid science? Eur. J. Oper. Res. 66, 184–203.

Roy B. 1996. *Multicriteria methodology for decision analysis*. Kluwer, Dordrecht.

Saaty, T.L., 1977. A scaling method for priorities in hierarchical structures. J. Math. Psychol. 15, 234–281. doi:http://doi.org/10.1016/0022-2496(77)90033-5

Saltelli, a, Tarantola, S., Chan, K., 1999. A Role for Sensitivity Analysis in Presenting the Results from MCDA Studies to Decision Makers. J. Multi-Criteria Decis. Anal. 145, 139–145.

Sánchez-Lozano, J.M., Henggeler Antunes, C., García-Cascales, M.S., Dias, L.C., 2014. GIS-based photovoltaic solar farms site selection using ELECTRE-TRI: Evaluating the case for Torre Pacheco, Murcia, Southeast of Spain. Renew. Energy 66, 478–494. doi:10.1016/j.renene.2013.12.038

The Society for Risk analysis (SRA) glossary, June 22, 2015 (http://www.sra.org/sites/default/files/pdf/SRA-glossary-approved22june2015-x.pdf)

Stecchi, F., Mancini, F., Ceppi, C., Gabbianelli, G., 2012. Vulnerability to ground deformation phenomena in the city of Tuzla (BiH): A GIS and multicriteria approach. Nat. Hazards 64, 2153–2165. doi:10.1007/s11069-012-0225-2

Tacnet, J.M., Dezert, J., Curt, C., Batton-Hubert, M., Chojnacki, E., 2014. How to manage natural risks in mountain areas in a context of imperfect information? New frameworks and paradigms for expert assessments and decision-making. Environ. Syst. Decis. 34, 288–311. doi:10.1007/s10669-014-9501-x

Tervonen, T., 2012. JSMAA: open source software for SMAA computations. Int. J. Syst. Sci. 45, 69–81. doi:10.1080/00207721.2012.659706

Thompson, S.S., Benn, D.I., Dennis, K., Luckman, A., 2012. A rapidly growing moraine-dammed glacial lake on Ngozumpa Glacier, Nepal. Geomorphology 145–146, 1–11. doi:10.1016/j.geomorph.2011.08.015

Vilímek, V., Klimeš, J., Emmer, A., Benešová, M., 2015. Geomorphologic impacts of the glacial lake outburst flood from Lake No . 513 (Peru). Environ. Earth Sci. 73, 5233–5244. doi:10.1007/s12665-014-3768-6

Vincent, C., Auclair, S., Meur, E. Le, 2010. Outburst flood hazard for glacier-dammed lac de Rochemelon, France. J. Glaciol. 56, 91–100. doi:10.3189/002214310791190857

Wang, W., Yao, T., Gao, Y., Yang, X., Kattel, D.B., 2011. A First-order Method to Identify Potentially Dangerous Glacial Lakes in a Region of the Southeastern Tibetan Plateau. Mt. Res. Dev. 31, 122–130. doi:10.1659/MRD-JOURNAL-D-10-00059.1

Wang, X., Liu, S., Guo, W., Xu, J., 2008. Assessment and Simulation of Glacier Lake Outburst Floods for Longbasaba and Pida Lakes, China. Mt. Res. Dev. 28, 310–317. doi:10.1659/mrd.0894

Wang, X., Liu, S., Ding, Y., Guo, W., Jiang, Z., Lin, J., Han, Y., 2012. An approach for estimating the breach probabilities of moraine-dammed lakes in the Chinese Himalayas using remote-sensing data. Nat. Hazards Earth Syst. Sci. 12, 3109–3122. doi:10.5194/nhess-12-3109-2012

Wang, X., Ding, Y., Liu, S., Jiang, L., Wu, K., Jiang, Z., Guo, W., 2013. Changes of glacial lakes and implications in Tian Shan, central Asia, based on remote sensing data from 1990 to 2010. Environ. Res. Lett. 8, 44052. doi:10.1088/1748-9326/8/4/044052

Wang, S., Qin, D., Xiao, C., 2015. Moraine-dammed lake distribution and outburst flood risk in the Chinese Himalaya. J. Glaciol. 61, 115–126. doi:10.3189/2015JoG14J097

Watson, C.S., Carrivick, J., Quincey, D., 2015. An improved method to represent DEM uncertainty in glacial lake outburst flood propagation using stochastic simulations. J. Hydrol. 529, 1373–1389. doi:10.1016/j.jhydrol.2015.08.046

Westoby, M.J., Glasser, N.F., Brasington, J., Hambrey, M.J., Quincey, D.J., Reynolds, J.M., 2014. Modelling outburst floods from moraine-dammed glacial lakes. Earth-Science Rev. 134, 137–159. doi:10.1016/j.earscirev.2014.03.009

Worni, R., Huggel, C., Stoffel, M., 2013. Glacial lakes in the Indian Himalayas--from an area-wide glacial lake inventory to on-site and modeling based risk assessment of critical glacial lakes. Sci. Total Environ. 468–469, S71-84. doi:10.1016/j.scitotenv.2012.11.043

Zapata, M. L., 2002. La dinamica glaciar en lagunas de la Cordillera Blanca, Acta Montana, 19, 37–60.

Zemp, M., Frey, H., Gärtner-Roer, I., Nussbaumer, S.U., Hoelzle, M., Paul, F., Haeberli, W., Denzinger, F., Ahlstrøm, A.P., Anderson, B., Bajracharya, S., Baroni, C., Braun, L.N., Càceres, B.E., Casassa, G., Cobos, G., Dàvila, L.R., Delgado Granados, H., Demuth, M.N., Espizua, L., Fischer, A., Fujita, K., Gadek, B., Ghazanfar, A., Hagen, J.O., Holmlund, P., Karimi, N., Li, Z., Pelto, M., Pitte, P., Popovnin, V. V., Portocarrero, C.A., Prinz, R., Sangewar, C. V., Severskiy, I., Sigurdsson, O., Soruco, A., Usubaliev, R., Vincent, C., 2015. Historically unprecedented global glacier decline in the early 21st century. J. Glaciol. 61, 745–762. doi:10.3189/2015JoG15J017

Supplementary data

Appendix A - Criteria description and threshold definition

Triggers

Regional seismic activity (TR.1)

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

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

Intense precipitation events and high temperature events have been combined in previous studies as the ‘hydrometeorological’ situation (Huggel et al., 2004; Wang et al., 2011), and such events have the capacity to trigger mass movements into a lake. Nevertheless, this does not offer the possibility to score each element of the criterion individually, indicating non-exhaustiveness. After splitting them into two separate criteria, the use of two global BIOCLIM indicators (BIO 4 - temperature seasonality; BIO 15 - precipitation seasonality) were considered as the most appropriate surrogates. Our rationale was that a more varied seasonal cycle in precipitation or temperature would be a reasonable proxy for how intense the precipitation or temperature events are. Precipitation seasonality is the measure of the variation in monthly precipitation totals over the course of the year. This index is the ratio of the standard deviation of the monthly total precipitation to the mean monthly total precipitation (also known as the coefficient of variation) and is expressed as a percentage; larger percentages represent greater variability of precipitation. We divided the three classes into <50% (low risk), which represents precipitation occurring roughly equally throughout the year, 50-100% (medium risk) representing seasonal precipitation, and >100% (high risk) which indicates precipitation occurring in less than three months in the year. Temperature seasonality indicates the amount of temperature variation over a given year (or averaged years) based on the standard deviation (variation) of monthly temperature averages. It is a measure of temperature change over the course of the year. The larger the standard deviation, the greater the variability of temperature. We have divided into three classes: <50% (low risk), 50-100% (medium risk), >100% (high risk). For extra information on these variables visit: https://pubs.usgs.gov/ds/691/ds691.pdf

Mechanisms

Dam freeboard (ME.1)

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

Dam type (ME.2)

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

Steepest slope surrounding lake (ME.3)

Mass movements entering a glacial lake are the main cause leading to GLOFs (Worni et al., 2013; Rounce et al., 2016). Steep slopes promote mass movements, which in turn can impact the lake and generate a flood wave that overtops or destroys the natural dam. Areas with a slope greater than 30° are susceptible to rock avalanches or landslides (Alean, 1985; Bolch et al., 2011; Rounce et al., 2016). Moreover, according to Alean (1985), temperate glaciers have been found to produce ice avalanches from a minimum slope of 25°, and cold-based glaciers from 45°. Therefore, we decided to consider 25° as the minimum threshold slope that can generate mass movements into a lake. Any lake that is not surrounded by a slope of at least 25° is not considered in the study. In addition, previous studies have considered only lakes within 500m of a glacier to be potential GLOF sources (e.g. Wang et al., 2011, 2015). Therefore, lakes that are further than 500m from a slope, or closer than 500m from a < 25° slope are not considered in this study. We defined three classes: <30° slope (low risk), 30-45° slope (medium risk) and >45° slope (high risk). The high-risk threshold is lowered to 30° for the sensitivity analysis in order to observe potential differences and risk class changes for the studied lakes.

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

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

Parent glacier snout steepness (ME.6)

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

Flood wave size/runout

Travel distance of GLOF (SR.1)

One of the main parameters for GLOF risk assessment is to estimate whether the flood wave can reach downstream communities. For this estimation, a ‘worst-case’ approach is followed (Huggel et al. 2002). Studies have analysed the runout characteristics of debris flows from glacier/moraine-dammed lakes in the European Alps. It has been found that debris flows generally abate when they reach a downstream average slope of 11° and clean flows when they reach 3° (Haeberli, 1983; Huggel et al., 2002; Hegglin and Huggel, 2008). The average slope angle is thereby defined as the slope of a line between the start and end point of an outburst event. Therefore, in this study we used the thresholds of 3-7° (low risk), 7-11° (medium risk), >11° (high risk). We encourage the use of the Modified Single-Flow direction model (MSF) for experienced users (Huggel et al., 2003), and a new version of this has been developed by Rounce et al. (2017b). Less experienced modellers may use Google Earth to find the average slope between the lake and potentially exposed communities or infrastructure.

Lake volume (SR.2)

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

Impact

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

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

Appendix B - Criteria values for lake evaluation

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

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