Remote assessment of Glacial Lake Outburst Flood risk using Multi-Criteria Decision Analysis

Ioannis Kougkoulos[1,2*], Simon J. Cook[2,3], Vincent Jomelli[4], Leon Clarke[1], Elias Simeonakis[1], Jason Dortch[2,5], Laura Edwards[2,6] and Myriam Merad[7,8]
[1]Manchester Metropolitan University, [2]Cryosphere Research at Manchester, [3]University of Dundee, [4]LGP-CNRS, [5]University of Manchester, [6]Liverpool John Moores University, [7]LAMSADE-CNRS, [8]ESPACE-CNRS
*Corresponding author e-mail: i.kougkoulos@mmu.ac.uk

Introduction

Glacial lake outburst floods (GLOFs) occur where the natural dam of a glacial lake is breached or overtopped. There have been significant population and infrastructure losses in the last decades from such events (**Fig 1,2**). Given the threat for local communities, many studies seek to estimate GLOF risk. One of the key shortcomings of such studies is that there is no consensus about what criteria should be assessed, in order to determine GLOF risk.

Multiple Criteria Decision Analysis (MCDA), is a method that provides a framework to determine a coherent set of criteria for making risk assessments. Whilst it has been applied in other natural risk/hazard contexts, it has not yet been applied to GLOFs. **Fig 3** was created after applying the guidlines shown in the **methods** section to all GLOF risk criteria stated in literature.

Aim: Provide an objective method to remotely assess GLOF risk (**Fig 4**).

Fig 1: Aftermath of GLOF in Keara, Bolivia, 2009

Photo: Martín Apaza Ticona

Fig 2: Emergency brigade, after GLOF in Almaty, Kazakhstan, 2015

Photo: Kazakhstan Ministry of Internal Affairs

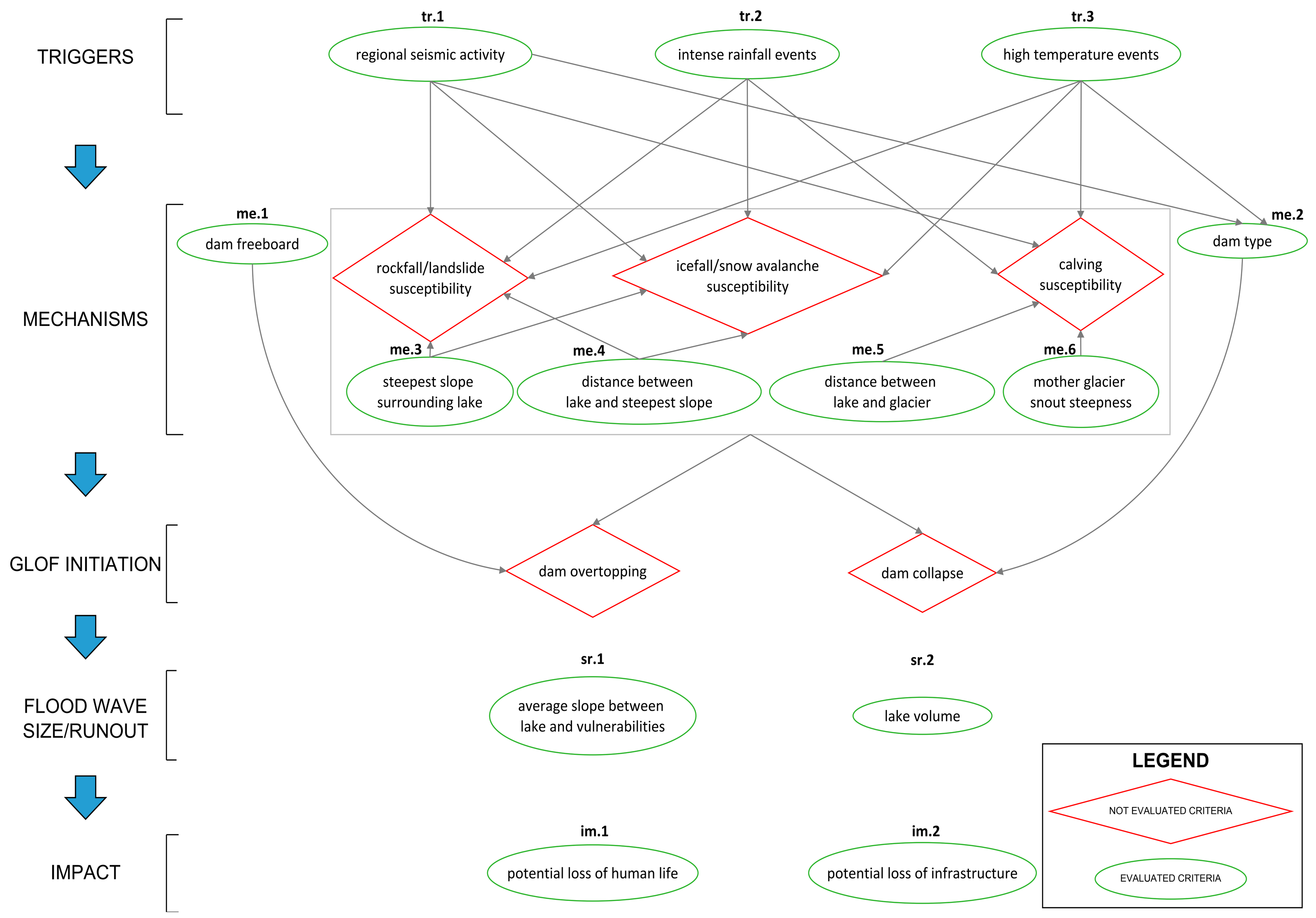

Fig 3: Flow diagram of the main criteria defining GLOF risk

Methods

The guidelines for the creation of a coherent set of criteria presented in **Fig 3** are listed below, accompanied by examples:

• **Exhaustiveness:** a criterion, such as rockfall/landslide susceptibility, is actually a composite of multiple criteria (e.g. slope steepness, seismic activity, etc.) (**Fig. 3**). Hence, such criteria need to be split into multiple separate criteria.

• **Non-redundancy:** For example, some assessments examine both glacier snout steepness and glacier snout crevassing, but these two criteria are actually strongly related - steeper slopes will generally lead to faster ice flow and crevassing.

• **Consistency:** For example, glacier shrinkage can have a two-way effect. For moraine-dammed lakes, glacier shrinkage will reduce the risk of calving or avalanches, but for ice-dammed lakes glacier shrinkage will increase the risk of GLOFs. Hence, criteria need to be selected such that their effects operate in the same direction.

STEP 1: Download the data and software

a) Most recent Landsat/Sentinel 2 images
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., 2008)
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 **Fig 1**
- the 3 risk categories (low/medium/high)

b) Assign a risk level for each criterion and lake (0=low; 2=medium; 4=high).

c) Run analysis

STEP 4: Apply solution to each lake

Check proposed solutions for each risk level

Fig 4: Flow diagram of the method

Results and discussion

MCDA was tested on 12 lakes already evaluated by Worni et al. (2013), Frey et al. (2016), Rounce et al. (2016) as well as on 5 past GLOFs and the results obtained are in agreement.

The set of criteria was then used to evaluate the risk of 18 lakes recently identified as being potentially dangerous by Cook et al. (2016) (**Fig 5, 6**):

• **15** lakes are classified as low risk and are not priorities for further detailed risk assessment.

• **2** lakes are classified as medium risk and a research focus should be given in the following years.

• **1** lake (Laguna Arkhata) presents high risk and should be the subject of urgent research into potential GLOF effects (e.g. hydrological modelling of GLOF runout).

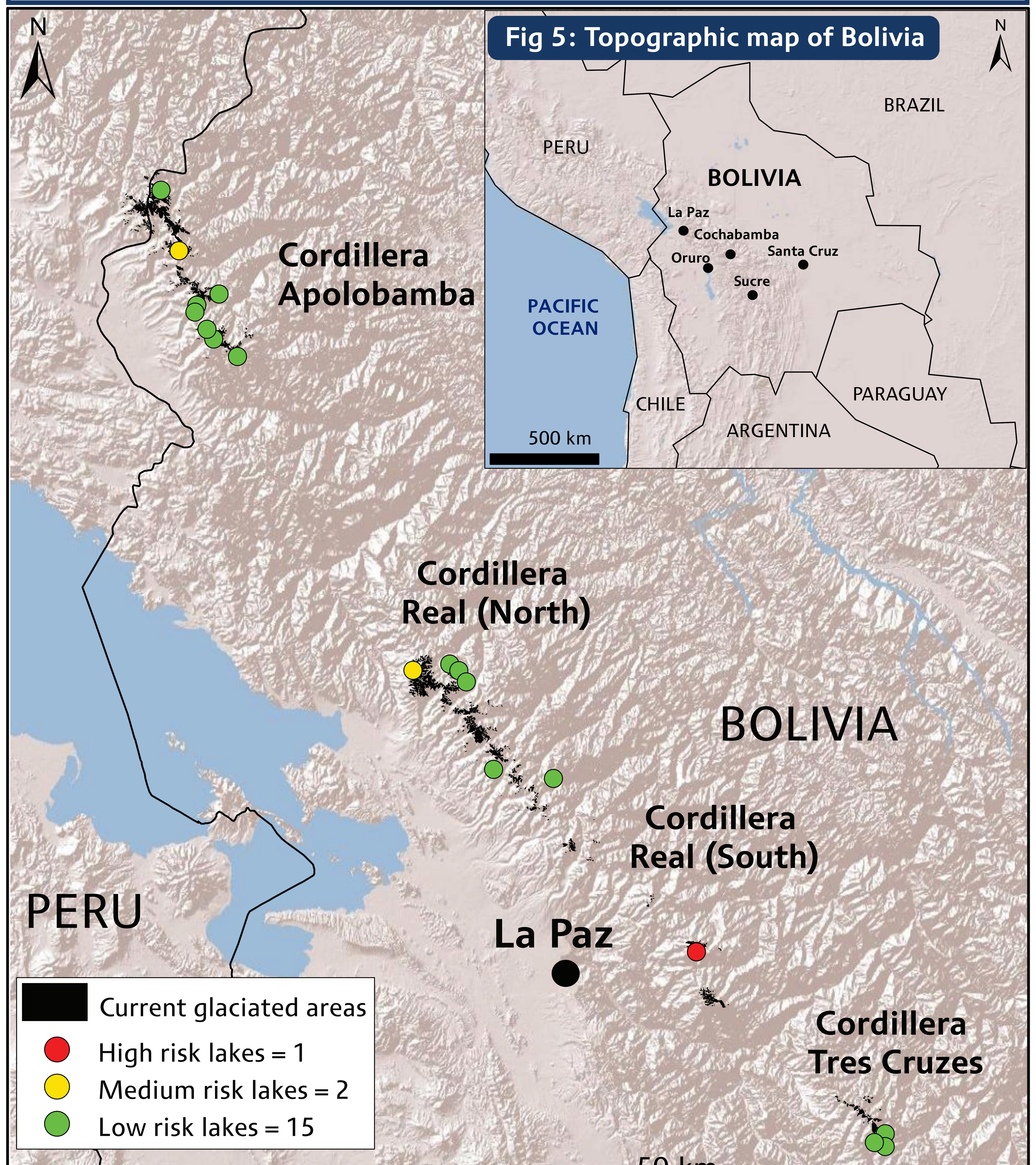

Fig 5: Topographic map of Bolivia

Fig 6: GLOF risk in the Bolivian Andes

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