New method for assessing the susceptibility of glacial lakes to outburst floods in the Cordillera Blanca, Peru

A. Emmer[1] and V. Vilímek[1]

[1]{Department of Physical Geography and Geoecology, Faculty of Science, Charles University in Prague, Czech Republic}

Correspondence to: A. Emmer (aemmer@seznam.cz)

Abstract

This paper presents a new and easily repeatable method for assessing the susceptibility of glacial lakes to the outburst floods (GLOFs) within the Peruvian region of the Cordillera Blanca. The presented method was designed to: (a) be repeatable (from the point of view of the demands on input data); (b) be reproducible (to provide an instructive guide for different assessors); (c) provide multiple results for different GLOF scenarios; and (d) be regionally-focused on the lakes of the Cordillera Blanca. Based on the input data gained from remotely-sensed images and digital terrain models / topographical maps, the susceptibility of glacial lakes to outburst floods is assessed using a combination of decision trees for clarity and numerical calculation limiting subjectivity for repeatability and reproducibility. A total of seventeen assessed characteristics are used, of which seven have not been used in this context before. Also, several ratios and calculations are defined for the first time. We assume that it is not relevant to represent the overall susceptibility of a particular lake to outburst floods by one result (number), thus it is described in the presented method by five separate results (representing five different GLOF scenarios). These are potentials for: (a) dam overtopping resulting from a fast slope movement into the lake; (b) dam overtopping following the flood wave originating in a lake situated upstream; (c) dam failure resulting from a fast slope movement into the lake; (d) dam failure following the flood wave originating in a lake situated upstream; and (e) dam failure following a strong earthquake. All of these potentials include two or three components and theoretically range from 0 to 1. The presented method was verified on the basis of assessing the pre-flood conditions of seven lakes which have produced ten glacial lake outburst floods in the past and ten lakes which have not. A

comparison of these results showed that the presented method successfully identified lakes susceptible to the outburst floods (pre-flood conditions of lakes which have already produced GLOFs).

1 Introduction

1.1 Phenomenon of GLOFs and the Cordillera Blanca

Glacial lakes of all types represent a significant threat for the inhabitants of high-mountain regions worldwide (e.g. Clague et al., 2012; Evans and Clague, 1994; Iribarren et al., 2014), including the most heavily glacierised tropical range of the world – the Cordillera Blanca of Peru (Carey, 2005; Vilímek et al., 2005). A sudden release of retained water causes floods, so-called “glacial lake outburst floods” – GLOFs, which can easily transform into the debris or mud flow movements (e.g. Breien et al., 2008; O'Connor et al., 2001). These extreme processes are characterised by discharges several times higher than the discharges reached during “classical” hydrometeorological floods (e.g. Cenderelli and Wohl, 2001; Costa and Schuster, 1988; Korup and Tweed, 2007). From the geomorphological point of view, these are one of the most significant fluvial / gravitational processes influencing glacial valleys in the period of deglaciation in high-mountain regions (Benn et al., 2012; Richardson and Reynolds, 2000a).

Since the end of the Little Ice Age, whose second peak culminated in the Cordillera Blanca in the 19th Century (Solomina et al., 2007; Thomson et al., 2000), catastrophic GLOFs originating from moraine-dammed and bedrock-dammed lakes have claimed thousands of lives and caused considerable damage within the region of the Cordillera Blanca (e.g. Ames and Francou, 1995; Carey et al. 2012; Lliboutry et al., 1977; Zapata, 2002). Many of the largest lakes have been remediated since the early 1950s (Carey, 2005), however the number of outburst floods has increased over the last decades. This fact is connected to the ongoing progressive deglaciation and to the associated increase in the overall number of lakes within the Cordillera Blanca (Emmer et al., 2014). Besides the formation and rapid evolution of new dangerous lakes, which is a result of glacier retreat (e.g. Quincey et al., 2007), the volume of already existing proglacial lakes often increases due to continuing glacier retreat beneath the water level or by lake deepening caused by melting of ice cores incorporated in submerged basal moraine (Vilímek et al., 2005). The greater the volume of water retained in the lake, the greater the volume of water available for potential flooding, depending on the cause and mechanism of water release (Westoby et al., 2014). Monitoring of glacier behaviour and repeated bathymetric measurements are thus quite important for registering the dynamic evolution of a particular lake.

Generally, there are three types of glacial lakes in the Cordillera Blanca, distinguished according to the dam material: (1) moraine-dammed; (2) bedrock-dammed; and (3) ice-dammed. In this article, ice-dammed lakes are excluded because they are not significant in number (on the contrary to the high mountains of Central Asia; Hewitt, K., 1982; Iturrizaga, 2005) and thus do not represent a threat, hence there is no need to take them into account in this context.

There are several causes and mechanisms of GLOFs (e.g. Clague and Evans, 2000; Costa and Schuster, 1988; Grabs and Hanisch, 1993; Richardson and Reynolds, 2000a; Westoby et al., 2014). Fast slope movements into the lake (icefall, landslide, or rockfall) producing a displacement wave, which may overtop or break the lake dam (depending on the particular dam type), are the main cause of GLOFs within the region of the Cordillera Blanca (Emmer and Cochachin, 2013). GLOFs following large earthquakes and GLOFs occurring when a flood wave originating from a lake situated upstream reaches a downstream situated lake were also recorded in this region (Lliboutry et al., 1977; Zapata, 2002). It is clear that the occurrence of GLOFs is a highly complex question, which, besides the lake and dam settings, is closely connected with the wider settings of the lake's surroundings (e.g. glaciological setting of the mother glacier, slope stability of moraines surrounding the lake, etc.). Assessing the possibility of GLOF occurrence (susceptibility of glacial lake to the outburst floods) is thus quite a challenging scientific problem, which requires an interdisciplinary approach as well as cooperation.

1.2 Previous research and existing methods for assessing the susceptibility of glacial lakes to outburst floods

Several methods for assessing the susceptibility of glacial lakes to outburst floods can be found in the literature (Bolch et al. 2011; Clague and Evans, 2000; Costa and Schuster, 1988; Grabs and Hanisch, 1993; Gruber and Mergili, 2013; Huggel et al., 2002, 2004; McKillop and Clague, 2007a,b; Mergili and Schneider, 2011; O'Connor et al., 2001; Reynolds, 2003; Wang et al., 2008; Wang et al., 2011; Wang et al., 2012; Yamada, 1993). These methods distinguish themselves by type of method construction, number and selection of assessed characteristics, required input data, and rate of subjectivity (Emmer and Vilímek, 2013). Some of them are regionally-focused and some are designed to be adaptable. The demands on the input data and the rate of subjectivity of methods are generally considered as the fundamental obstructions to their repeated use. Emmer and Vilímek (2013) examined the suitability of these methods for use within the Cordillera Blanca. It was shown that none of the applied methods meet all of the specified criteria, therefore a new method is desirable (see 1.3). Once lakes susceptible to the outburst floods are identified, flood modelling and delimitation of endangered areas are the next steps in the risk management procedure (Westoby et al., 2014; Worni et al., 2013).

1.3 Reasons and objectives of the study

The reasons of the presented study are: firstly, as shown in our previous research - existing methods are not wholly suitable for use within the Cordillera Blanca from the perspective of the assessed characteristics and the account of regional specifics (especially the share and representation of various triggers of GLOFs, climate settings; Emmer and Cochachin, 2013; Emmer and Vilímek, 2013). Secondly, the majority of these methods are at least partly subjective (based on an expert assessment without giving any thresholds), thus different observers may reach different results even when the same input data are used. Repeated use is thus considerably limited and we consider this to be the fundamental drawback of the present methods as well as a research deficit.

Due to the above-mentioned reasons, the main objective of this work is to provide a comprehensive and easily repeatable methodological concept for the assessment of the susceptibility of glacial lakes within the Cordillera Blanca to the outburst floods, verified on the glacial lakes and GLOFs recorded in this region. The impacts of glacial lake outburst floods cannot ever been completely eliminated; nevertheless, reliable assessment of the susceptibility of glacial lakes to the outburst floods is a necessary step in the effective flood hazard and consequently risk management and mitigation, therefore it is of great importance.

2 Creation of new method

The presented method is designed to meet four principles which were considered as being crucial based on an analysis of the drawbacks of the existing methods (Emmer and Vilímek, 2013). The presented method is designed to: (a) be repeatable (from the point of view of the demands on input data; all input data are gained from remotely-sensed images and digital terrain models or topographical maps, there is no need for field survey); (b) be reproducible (the presented method provides an instructive guide for different assessors, which should obtain identical results should the same input data be used); (c) provide multiple results for different GLOF scenarios (multiple results provide a more detailed view of the susceptibility of an assessed lake to outburst floods and also allow any gaps in the availability of the input data to be filled. The principle of multiple results also allows individual characteristics important in each scenario to be targeted); and (d) be regionally-focused on the lakes of the Cordillera Blanca (method verification on the lakes of this range).

Creation of a new method for assessing the susceptibility of glacial lakes to outburst floods generally requires four stages, which reflect the structure of the presented paper. These are: (1) selection of the type of construction of the method; (2) selection of the appropriate characteristics to be assessed (this stage includes analysis of regional specifics and also subordination to the data availability); (3) determination of thresholds and weightings of the assessed characteristics (it is essential to determine the thresholds (critical values) because of the reproducibility of the method used); and (4) method verification.

2.1 Type of construction of the method

Each method for assessing the susceptibility of glacial lakes to outburst floods usually has its own specific construction. Generally, we can distinguish between: (1) points-based methods, where susceptibility to GLOFs is indicated by the number of achieved points (e.g. Huggel et al., 2002; Reynolds, 2003); (2) calculation-based methods, where susceptibility to GLOFs is based on the results of defined calculations (e.g. McKillop and Clague, 2007; Wang et al, 2011); (3) decision tree-based methods, where an instructive graphical guide for assessment is given (e.g. the presented method); (4) matrix-based methods, which are usually used in combination with e.g. the point-based method and the overall susceptibility is derived from two or more components (e.g. Mergili and Schneider, 2011); and (5) their combinations. A combination of decision trees for clear illustrative representation of the assessment procedures and calculations for clarity and simple repeatability was used in the presented method.

Recorded mechanisms of GLOFs within the Cordillera Blanca of Peru (Emmer and Cochachin, 2013) have been shown to be dam overtopping or dam failure (only in case of moraine-dammed lakes), both following various triggers. Therefore, we feel it is necessary to strictly distinguish between these two dissimilar mechanisms in the assessment the susceptibility of glacial lakes to outburst floods, because the processes affecting the characteristics and also volumes of released water significantly differ. Dam overtopping within the Cordillera Blanca has been described as a result of: (a) fast slope movement into the lake; or (b) flood wave from a lake situated upstream. Dam failures have been described as a result of: (a) fast slope movement into the lake; (b) flood wave from a lake situated upstream; or (c) a strong earthquake.

We feel it is not meaningful to describe the overall susceptibility of a particular lake to outburst floods with the use of a single number, as has been done by many authors before. The presented method thus assesses the potentials for the five above-mentioned scenarios separately, whereby providing five separate results. These results are designed as a product of two or three components for each scenario (Tab. 1). Richardson and Reynolds (2000a) showed that it is necessary to include two components: (a) dam stability; and (b) potential for initializing event. This more or less corresponds to the components presented in this method. It is clear that some of the scenarios include similar components, e.g. both Scenario 1 and Scenario 3 include the components “potential for fast slope movement into the lake” and “potential for dam overtopping by displacement wave”; however, Scenario 3 also includes the component “dam erodibility”.

The obtained results theoretically range from 0 to 1 for each component and thus also from 0 (zero potential) to 1 (maximal potential) for each scenario. Naturally, this allows for both the identification of the most susceptible lakes and the most likely scenario of the outburst flood for a particular lake (scenario with the highest potential).

2.2 Assessed characteristics and their thresholds

According to the previous research (Emmer and Cochachin, 2013; Emmer and Vilímek, 2013), five essential groups of characteristics which need to be taken into account in a regionally focused method for assessing the susceptibility of glacial lakes to outburst floods within the Cordillera Blanca were estimated. These are groups of characteristics related to: (a) the possibility of fast slope movement into the lake; (b) the distinction between a natural dam and a dam with remedial works (more generally dam stability); (c) the dam freeboard (ratio of dam freeboard); (d) the possibility of a flood wave from a lake situated upstream; and (e) the possibility of a dam rupture following a large earthquake.

Individually assessed characteristics in the new method (requiring input data) were chosen to meet the following criteria: (1) they fit into the five above-mentioned groups of characteristics; and (2) they are subordinated to data availability. Some of the characteristics were repeated in several of the scenarios (e.g. dam freeboard for Scenarios 1-4) and some are specific for an individual scenario (e.g. piping for Scenario 5). Most of the characteristics have already been mentioned in previous studies but we have also used seven characteristics which have not been mentioned in this context before (Tab. 2).

Objective determination of thresholds is quite a delicate scientific problem, on the other hand it is highly desirable to determine all of the thresholds in order to eliminate the subjective component (presence of an "expert assessment") and for repeatability of the method (see also 4.1). We aimed to eliminate the need of threshold estimation, thus continuous variables and various ratios were used as much as possible. It is clear that it is not wholly possible to limit or quantify qualitative discrete variables (e.g. dam type, piping occurrence, or type of remedial work). Therefore, qualitative discrete variables are used in the decision trees, but not in the calculations.

2.3 Decision trees and calculations

As we have explained above, five separate assessment procedures (decision trees) for five different GLOF scenarios are included in the presented method. These are: (a) potential for dam overtopping resulting from a fast slope movement into the lake (see 2.3.1); (b) potential for dam overtopping following the flood wave originating in a lake situated upstream (see 2.3.2); (c) potential for dam failure resulting from fast slope movement into the lake (see 2.3.3); (d) potential for dam failure following the flood wave originating in a lake situated upstream (see 2.3.4); (e) potential for dam failure following a strong earthquake (see 2.3.5). The first and second scenarios (dam overtopping) are possible for all lake types, whereas the other scenarios (dam failures) may occur exclusively in the case of moraine-dammed lakes.

2.3.1 Potential for dam overtopping resulting from fast slope movement into the lake (Scenario 1)

It has been shown that GLOFs most frequently result from fast slope movement into the lake, producing a displacement wave (e.g. Costa and Schuster, 1998; Clague and Evans, 2000; Awal et al., 2010). There are two components that need to be taken into consideration when assessing the potential for Scenario 1. These are: (a) potential for fast slope movement into the lake; and (b) potential for dam overtopping by a displacement wave. The overall potential for Scenario 1 is consequently derived by combining both of these components.

The group of characteristics describing the first component includes characteristics related to the various types of fast slope movements, which may enter the lake and consequently cause a displacement wave resulting in dam overtopping. These are especially characteristics related to the possibility of: (a) calving into the lake; (b) icefalls from hanging glaciers into the lake; and (c) landslides on moraines surrounding the lake. Thus, the first component includes three subcomponents. For the final assessment of the Scenario 1, the higher subcomponent is used.

The first step in assessing the potential for icefall into the lake is to determine whether a glacier is situated above the lake or the valley is already completely deglaciated. If the valley is already completely deglaciated, the potential for icefall into the lake is naturally equal to 0. If there are glaciers above the lake, the first of the assessed characteristics related to the potential for icefalls from calving or hanging glaciers into the lake is the distance between the lake and the glacier (D_{is} = [m]). This characteristic provides information on whether the lake is in direct contact with the glacier (calving occurs) or not. If the assessed lake is in direct contact with a glacier (D_{is} = 0 m), then the ratio of the width of the calving front to the maximal lake width ($r_{\mathrm{Clw/Lw}}$ = [unitless]) is calculated as follows:

$$r_{\mathrm{Clw/Lw}} = C_{\mathrm{lw}} / L_{\mathrm{w}} \qquad (1)$$

where C_{lw} is the width of the calving front (C_{lw} = [m]) and Lw is the maximal lake width (L_{w} = [m]). Ratio $r_{\mathrm{Clw/Lw}}$ is used to simplistically describe the potential for an appearance of a displacement wave(s) induced by the falling of part of the front of a calving glacier into the lake, with limited demand on input data (see 4.1; 4.3). It is clear that the potential increases with an increasing width of the calving front. In order to obtain a dimensionless value we decided to relate the width of the calving front to the maximal lake width. The potential for icefall into the lake is equal to 1 if the ratio of the width of the calving front to the maximal lake width is equal or greater to 1. If it is less than 1, then the resulting value is used as the potential for icefall into the lake (Fig. 1).

If the lake is not in direct contact with the glacier ($D_{is} > 0$ m), the topographical susceptibility for icefall (T_{SI} = [unitless]) should be calculated as follows:

$$T_{SI} = \sin(S_{LG}) \cdot \sin(S_{G500}) \qquad (2)$$

where the mean slope between the lake and the glacier (S_{LG} = [°]) and the mean slope of the last 500 m of the glacier tongue (S_{G500} = [°]) are used. A sinus function was chosen to describe the non-linear increasing potential with increasing slope. The second reason for selecting a sinus function was that we believe that it is more important to stress the rapidly increasing susceptibility of the slopes between 0°-60° than between 60°-90° because moraine slopes steeper than 70° frequently fail. For this reason a tangent function which stresses differences between steeper slopes was not used. We feel that it is not necessary to include the distance between the lake and the glacier in the equation, because the question of whether a broken block of ice will finally hit the lake or not is primarily controlled by the slope between the lake and the glacier. Moreover, the distance between the lake and the glacier is used in the previous step in the decision tree.

To assess the potential for a landslide of a moraine into the lake, it is first necessary to decide whether there are unstable moraine slopes in the lake surroundings. It is recommended to make a decision on the basis of manual expert analysis of high resolution optical images, or geomorphological (geological) maps, if available. If there are moraines surrounding the lake, then the potential for a landslide into the lake is described by a single characteristic in the presented method, as follows:

$$T_{SL} = \sin(S_{Mmax}) \qquad (3)$$

where S_{Mmax} is the maximal slope of a moraine surrounding the lake (S_{Mmax} = [°]). We suppose that the use of the maximal slope instead of the mean slope, which is generally used, is more representative for this assessment procedure, because the possibility of a landslide occurrence is generally not controlled by the mean slope but by the maximal slope. The decision tree describing the procedure for assessing the potential for fast slope movement into the lake provides three results: potential for calving into the lake, potential for icefall from hanging glaciers into the lake and potential for a landslide of a moraine into the lake. The higher value is typically used for the final assessment of the potential for dam overtopping following fast slope movement into the lake, but each of the values can be used to estimate the potential for each specific trigger.

The second component for assessing the potential for dam overtopping following fast slope movement into the lake is the potential for dam overtopping by a displacement wave. It is necessary to decide whether the displacement wave generated by the slope movement into the lake would overcome the dam freeboard (D_f - vertical distance between the lake level and the lowest point on the dam crest; D_f= [m]) or would be captured within the lake. The first step in this part of the decision tree is therefore an assessment of the dam freeboard. If the assessed lake has surface outflow ($D_f = 0$ m), then the potential for dam overtopping following fast slope movement into the lake is maximal (=1). If $D_f > 0$ m, the ratio of dam freeboard to the cube root of the lake volume ($r_{Df/V}$) is calculated (see Eq. 5). This ratio was chosen for several reasons. Firstly, this ratio provides a continuous variable therefore it is not necessary to determine any thresholds. Secondly, this ratio increases with increasing dam freeboard and decreases with the same dam freeboard and greater lake volume. Thirdly, there is no need to estimate the volume of potential slope movement.

It is clear that the lake volume is an essential input value for the calculation of dam freeboard to the cube root of the lake volume ratio. The relation between lake surface area (A = [m^2]) and lake volume (V = [m^3]) of 35 glacial lakes of various types (both moraine-dammed lakes and bedrock-dammed lakes) and sizes (from $0.02 \cdot 10^6$ m^3 to $49.63 \cdot 10^6$ m^3) within the Cordillera Blanca was used for this purpose. Input data were gained from Autoridad Nacional del Agua bathymetries (Cochachin et al., 2010; Cochachin and Torrés, 2011). The empirical power function formula for deriving lake volume (V) from easily measured lake surface area (A) was estimated as follows:

$$V = 0.054293 \cdot A^{1.483009} \qquad (r^2=0,927) \qquad (4)$$

where A is the lake surface area (A = [m^2]). This formula is used for calculating all of the lake volumes in the presented method because the bathymetry of the majority of the glacial lakes within the Cordillera Blanca is not measured. With this input data it is possible to calculate the ratio of dam freeboard to the cube root of lake volume ($r_{\mathrm{Df/V}}$ = [unitless]) as follows:

$$r_{\mathrm{Df/V}} = D_{\mathrm{f}} / V^{1/3} \tag{5}$$

where D_{f} is dam freeboard (D_{f} = [m]); and V is lake volume (V = [m^3]; Eq. (4)). The cube root function was used for the purpose of unifying the units.

2.3.2 Potential for dam overtopping following the flood wave originating in a lake situated upstream (Scenario 2)

An outburst flood following Scenario 2 is possible in the cascade systems of the lakes within the Cordillera Blanca. Hand in hand with ongoing deglaciation, new unstable lakes at high elevation about 5 000 m a.s.l. are forming and rapidly growing (Emmer et al., 2014) and pose possible triggers for outburst floods from lakes situated downstream (large lakes in main valleys).

Assessment of the potential for Scenario 2 generally requires the following two components to be included: (a) retention potential of a lake situated downstream (assessed lake); (b) potential for a flood wave from a lake situated upstream. Due to their interconnection and for reasons of clarity, both of these components are incorporated in the decision tree simultaneously (are not distinguished) (Fig. 2). The presented method is not designed to take into account the retention potential of the valley between two consecutive lakes. This is especially due to the fact that this question is quite complex and requires its own assessment procedure with high demands on input data. Therefore, we assume the distribution of all of the escaped water from the upstream situated lake into the downstream situated lake. If the upstream situated lake is considered to pose a threat to a downstream situated lake, then we recommend more detailed investigation in order to quantify the retention potential of the valley between the lakes and the flood modelling.

An assessment of the potential for Scenario 2 is only meaningful when the ratio of the upstream lake volume to downstream lake retention potential ($r_{\mathrm{V/Vret}}$; = [unitless]) is higher than 1 (see Fig. 2). This ratio describes whether the lake volume of the upstream situated lake is greater than the retention potential of the downstream situated (assessed) lake or not.

In this ratio, Eq. (4) is used for estimating the volume of the upstream situated lake(s). The second component of the ratio is the retention potential of a downstream situated (assessed) lake (V_{ret} = [m^3]). Based on a simplified geometric model of the lake, the formula for calculating the retention potential was estimated as follows:

$$V_{\mathrm{ret}} = D_{\mathrm{f}} \cdot (6A + D_{\mathrm{f}} \cdot tg(90-\alpha)(3L_{\mathrm{lac}} + 2\pi \cdot D_{\mathrm{f}} \cdot tg(90-\alpha)))/6 \qquad (6)$$

where D_{f} is the dam freeboard (D_{f} =[m]); A is the lake surface area (A = [m^2]); L_{lac} is the lake perimeter (L_{lac} = [m]); α is the mean slope of the lake surroundings (α = [°]). Eq. (6) is used to quantify the maximum absorbable volume of water before the dam crest is reached (the retention potential of the lake), assuming a gradual increase in water level (not assuming the possibility of the appearance of a significant displacement wave caused by the flood wave from the upstream situated lake). The ratio of the upstream lake volume to the downstream lake retention potential has the following form:

$$r_{\mathrm{V/Vret}} = V / V_{\mathrm{ret}} \qquad (7)$$

where V is the volume of the lake situated upstream (V = [m^3]; Eq. (4)), and V_{ret} is the retention potential of the lake situated downstream (V_{ret} = [m^3]; Eq. (6)). The result of the upstream lake volume to downstream lake retention potential ratio calculation is limited: $0 < r_{\mathrm{V/Vret}} < \infty$. If the lake volume of the lake situated upstream is higher than the retention potential of the lake situated downstream ($r_{\mathrm{V/Vret}} > 1$), then the flood wave originating from this upstream lake may subsequently also cause an outburst flood from the lake situated downstream. In this case, it is necessary to assess the susceptibility of the upstream situated lake to an outburst flood separately. The potential for dam overtopping is therefore equal to the susceptibility of the upstream situated lake to the outburst flood (the whole assessment procedure is needed). In cases where the retention potential of a downstream situated lake is higher than the volume of upstream situated lake, the potential flood wave would be absorbed by the downstream situated lake and the potential for dam overtopping is thus equal to zero (Fig. 2).

It is clear that the calculation of $r_{\mathrm{V/Vret}}$ is not relevant for lakes with surface outflow (D_{f} = 0 m; V_{ret} = 0; $r_{\mathrm{V/Vret}} \rightarrow \infty$). In these cases, it is necessary to estimate the minimal volume or the critical lake area (A_{crit} = [m^2]), which needs a separate assessment procedure (to avoid assessing all of the small lakes situated upstream). For this purpose, a simple equation was estimated:

$$A_{\mathrm{crit}} = 0.05 \cdot A \qquad (8)$$

where A is the surface area of the assessed lake (A = [m^2]). A constant (0.05) was chosen on the basis of analyzing previous events (e.g. the 2012 event in Artizon (Santa Cruz) valley; Emmer et al. 2014) and expert assessment. For the sake of reproducibility of the method, this constant needed to be estimated, even if in a partly subjective way (see also 4.1). Should a lake situated upstream exceed the calculated critical lake area, then it is necessary to assess the susceptibility of this lake to an outburst flood separately (whole procedure). The potential for Scenario 2 of the assessed downstream situated lake is then equal to this result (Fig. 2).

2.3.3 Potential for dam failure resulting from fast slope movement into the lake (Scenario 3)

As it was mentioned in the introduction, an assessment of the potential for Scenario 3 requires the same procedure as the assessment of the potential for Scenario 1, with the difference being that the dam erodibility has to be taken into consideration. This term is used to describe the “immunity” of a moraine dam (its outflow) to the extreme flow rate resulting from a displacement wave overtopping a moraine crest.

Therefore, three components need to be incorporated (Tab. 1): (a) potential for fast slope movement into the lake; (b) potential for dam overtopping by a displacement wave; and (c) dam erodibility. The overall potential for Scenario 3 is calculated as a product of these three components and the overall procedure is shown in detail in Fig. 3. The procedure for estimating the components (a) and (b) is similar to the one described in the first scenario (Fig. 1).

For estimating dam erodibility (third component) on the basis of remotely-sensed high resolution images and digital terrain model (DTM) or topographical maps, without any field survey, it is generally necessary to include the characteristics describing dam material, dam geometry and peak discharge. With reduced demands on input data, the dam material is only characterised by dam type (moraine dam x bedrock dam). Dam geometry is represented by the maximal slope of the distal face of the dam (S_{DFDmax}; see below) and peak discharge is calculated in the form of a peak discharge factor (P_{DF}). The calculation of the peak discharge factor is different for the different scenarios. Therefore, P_{DFS3} is used for Scenario 3, while P_{DFS4} is used in Scenario 4 (see 2.3.4; Eq. (11)).

The presented method does not quantify the volume of potential slope movement(s) into the lake, thus P_{DFS3} is designed to simplistically describe the peak discharge for an idealised unitary fast slope movement into the lake. In this scenario, P_{DFS3} is calculated as follows:

$$P_{\mathrm{DFS3}} = 1 - r_{\mathrm{Df/v}} \tag{9}$$

where $r_{\mathrm{Df/V}}$ is the ratio of the dam freeboard to the cube root of the lake volume ($r_{\mathrm{Df/V}}$ = [unitless]; Eq. (5)). After that, erodibility of the dam for Scenario 3 (E_{RDBS3}) is estimated as follows:

$$E_{\mathrm{RDBS3}} = \sin(S_{\mathrm{DFDmax}}) \cdot P_{\mathrm{DFS3}} \tag{10}$$

where S_{DFDmax} is the maximal slope of the distal face of the dam (S_{DFDmax} = [°]), simplistically describing the dam geometry and thus susceptibility to erosion (erodibility). The maximal slope of the distal face of the moraine was used to capture the most vulnerable part of the moraine dam as we suppose that this is more predicative than the use of the mean slope (in contrary to methods presented by Wang et al., 2008; Wang et al., 2011; and Mergilli and Schneider, 2011). Without the need for field survey, we can assume a uniform internal composition of different moraine dams. P_{DFS3} is the peak discharge factor for Scenario 3 (P_{DFS3} = [unitless]; Eq. (9)). Therefore the erodibility of the dam in the presented method is only dependent on: (a) the maximal slope of the distal face of the dam; and (b) the peak discharge factor.

2.3.4 Potential for dam failure following a flood wave originating in a lake situated upstream (Scenario 4)

It is generally necessary to take three components into account for a meaningful assessment of the potential for the Scenario 4 (see Tab. 1). These are: (a) retention potential of a lake situated downstream (assessed lake); (b) potential for a flood wave from a lake situated upstream; and (c) dam erodibility of a downstream situated (assessed) lake. The overall procedure (decision tree) for assessing the potential for Scenario 4 is described in Fig. 4. The procedure for the estimation of components (a) and (b) is similar to the one described in the Scenario 2 (see 2.3.2; Fig. 2).

Analogically to the previous scenario, dam failure may only occur in the case of moraine-dammed lakes. Therefore, the first step in assessing the potential for Scenario 4 is to distinguish between the different dam types (Fig. 4). The peak discharge factor for Scenario 4 (dam failure following a flood wave originating in a lake situated upstream) is calculated as follows:

$$P_{\mathrm{DFS4}} = ((V - V_{\mathrm{ret}}) / A)^2 \tag{11}$$

where V is the volume of the lake situated upstream (V = [m^3]; Eq. (4)), V_{ret} is the retention potential of a downstream situated (assessed) lake (V_{ret} = [m^3]; Eq. (6)), and A is the area of the assessed lake (A = [m^2]). The peak discharge factor (P_{DFS4} = [m^2]) is designed to substitute the peak discharge, which can be generally expressed as a product of the cross-section area and flow velocity. The flow velocity is not known, thus P_{DFS4} is based only on the cross-section area of the flow. The power of two was used to stress that the cross-section area and the peak discharge increase exponentially with an increase in the water level, which is expressed as (V - V_{ret} /A; [m]). If $P_{\mathrm{DFS4}} > 1$, $P_{\mathrm{DFS4}} = 1$ is used in the following calculation of dam erodibility for Scenario 4 (E_{RDBS4} = [unitless]):

$$E_{\mathrm{RDBS4}} = \sin(S_{\mathrm{DFDmax}}) \cdot P_{\mathrm{DFS4}} \tag{12}$$

where S_{DFDmax} is the maximal slope of the distal face of the dam (S_{DFDmax} = [°]), and P_{DFS4} is the peak discharge factor for Scenario 4 (P_{DFS4} = [unitless]; Eq. (11)). Analogically to Scenario 2, in the presented method we assume a gradual increase in the water level in the downstream situated lake rather than the formation of the significant displacement wave. The retention potential of the valley between the consecutive lakes is also not considered.

2.3.5 Potential for dam failure following a strong earthquake (Scenario 5)

An assessment of the potential for Scenario 5 requires two components to be included (see Tab. 1). These are: (a) potential for a strong earthquake; and (b) dam instability. The Cordillera Blanca is generally considered to be one of the seismically most active high mountain regions of the contemporary world. It is clear that the potential for a strong earthquake in comparison with other regions of the world needs deeper evaluation; on the other hand, the potential for a strong earthquake on a regional scale (assessing the differences between each parts of this mountain range) is not needed. A South American seismic hazard map presented by USGS (Giardini et al., 1999; Rhea et al., 2010) shows that whole region of the Cordillera Blanca is categorized as a zone with maximal peak ground acceleration (PGA) of between 3.2 to 6.4 m/s^2. Although most earthquakes have their origin in the subduction zone of the Pacific Ocean, we suppose that there is no significant difference in the maximal PGA between the west and east side of the Cordillera Blanca. Therefore, the whole region of the Cordillera Blanca has an equivalent (similar) potential for strong earthquakes and it is not necessary to take characteristics of potential earthquake into account on a regional scale during the assessment of the susceptibility of glacial lakes to outburst floods in the presented method. Thus, the first component in the assessment of the potential for dam failure following a strong earthquake (potential for strong earthquake) is always equal to 1 (the whole region is susceptible to a strong earthquake).

The second component (dam instability) firstly requires an assessment of dam type. It is clear that dam failure following a strong earthquake is not a possible scenario for bedrock-dammed lakes, because bedrock dams are generally considered to be stable (dam instability = 0 and overall potential for dam failure following a strong earthquake = 0; see Fig. 5).

It has been shown that moraine dam failure following a strong earthquake occurs due to changes in the internal structure of the dam and consequent internal erosion (piping), which cyclically increases its rate due to the increasing discharge (positive feedback mechanism; Lliboutry et al., 1977; Yamada, 1998). In extreme cases, increasing piping may lead to dam rupture. Therefore, a crucial characteristic in assessing the potential for dam failure following a strong earthquake is information about the internal structure of the dam, represented in this study by piping through the dam. If piping occurs, the estimation of dam instability (D_I = [unitless]) requires the following procedure, which starts with a calculation of the ratio between the dam height and the dam width ($\mathrm{r}_{\mathrm{Dh/Dw}}$ =[unitless]) as follows:

$$r_{\mathrm{Dh/Dw}} = D_{\mathrm{h}} / D_{\mathrm{w}} \tag{13}$$

where D_{h} is dam height (D_{h} = [m]), Dw is dam width (D_{w} = [m]). Then, dam instability (D_{I} = [unitless]) is calculated as follows:

$$D_{\mathrm{I}} = r_{\mathrm{Dh/Dw}} \cdot \sin(2\gamma) \tag{14}$$

where $\mathrm{r}_{\mathrm{Dw/Dh}}$ is the ratio between the dam height and the dam width ($r_{\mathrm{Dh/Dw}}$ = [unitless]; Eq. (13)), and γ is the piping gradient (γ = [°]). The piping gradient provides information about the slope between the lake water level and piping springs. A double value is used to emphasize the role of γ, which is rarely higher than 20°. In the case that there is no evidence of piping, dam instability (D_{I} = [unitless]) is calculated as follows:

$$D_{\mathrm{I}} = r_{\mathrm{Dh/Dw}}{}^{2} \tag{15}$$

where $r_{\mathrm{Dh/Dw}}$ is the ratio between the dam height and the dam width ($r_{\mathrm{Dh/Dw}}$ =[unitless]; Eq. (13)). The power of two of $r_{\mathrm{Dh/Dw}}$ was used to emphasise that no piping occurs (to stress dam geometry).

2.4 Input data

The presented method is designed to provide a repeatable methodological concept for assessing the susceptibility of a high number of lakes to outburst floods, with a limited demand on input data. We believe that the method for assessing the susceptibility of glacial lakes to outburst floods and incorporating the assessed characteristics should always be partly subordinated to data availability, in order to provide applicability and repeatability of the method. The presented method focuses on a wide range of users and thus is designed for broadly available input data. All of the assessed characteristics are easily driveable from high resolution optical images (e.g. Google Earth Digital Globe 2014) and digital terrain models (topographical maps). Characteristics which need field survey (e.g. geological setting, detailed glaciological setting or characteristics describing the internal dam structure such as buried ice presence/absence) are not incorporated.

3 Method verification

3.1 General principle

It is always highly important to verify the relevance of a new method, to prove its functionality. The main idea of the presented method verification is the assessment of the susceptibility of several lakes to outburst floods, of which some have produced GLOFs since the end of Little Ice Age (Tab. 3) and some have not. Seven lakes from the region of the Cordillera Blanca, which have produced ten GLOFs, were selected so that different lake types, different causes and different scenarios of GLOFs are represented. Another criterion was data availability for historical events (scientific publications, aerial photos, reports from ANA archive (Huaráz, Peru)). Ten lakes which have yet to produce a GLOF were chosen to be assessed to prove the presented method in comparison with GLOF-producing lakes. These ten lakes were selected so that different lake types and settings are represented. Therefore, a total number of twenty lakes (pre-flood conditions respectively) were examined.

An assessment of the pre-flood conditions of the lakes which have already produced GLOFs should show whether the presented method allows us to identify the most likely GLOF scenario for a particular lake (comparison with real cause) and if these lakes will have a higher potential than lakes which have yet to produce GLOFs. A comparison between the pre-GLOF conditions of the lakes which have produced GLOFs with those which have not should highlight the most susceptible lakes for each scenario. The assumption is that the presented method should clearly distinguish between lakes which have already produced GLOFs and those which have not.

3.2 Input data

Input data for assessing the pre-GLOF conditions of the examined events as well as input data for assessing the susceptibility of lakes which have yet to produce GLOFs were gained from various sources: (a) remotely sensed images (Google Earth Digital Globe 2014 covering the Cordillera Blanca region since 1970; three sets of old aerial photographs for the periods 1948-1950, 1962-1963 and 1970); (b) unpublished research reports from the archive of Autoridad National del Agua (Huaráz, Peru); (c) data and information gained during a field survey performed in May/June 2012, June/July 2013 and May/June 2014; and (d) contemporary and historical ground-based photos from the studied sites. A comprehensive list of input data used for the assessment is presented in the Supplement.

3.3 Results

The results of the method can generally be verified from two points of view: (a) the most likely scenario for a particular lake; and (b) the most susceptible lake for each scenario. A combination of both of these results provides quite a good overview of the susceptibility of the examined lakes to outburst floods.

3.3.1 The most likely scenario for a particular lake

Verification of the most likely scenario of a GLOF for particular lake is relevant only in the case of lakes which have already produced GLOFs (7 lakes, 10 examined pre-flood conditions). It is important to stress that the potential for Scenario 1 and Scenario 2 (dam overtopping) is always higher than or equal to the potential for Scenario 3 and Scenario 4 respectively, because dam overtopping is a prerequisite for dam failure. We feel it is relevant to distinguish between these mechanisms of GLOFs because of subsequent flood modelling and an estimation of the volume of potentially released water.

The presented method successfully identified real GLOF triggers in 9 out of 10 cases (the only exception was the Lake Safuna Alta 1970 event; see Tab. 4). The condition of Lake Safuna Alta before a catastrophic earthquake occurred on the 31st of May 1970 indicated that the most likely GLOF scenario was Scenario 1 (dam overtopping by a displacement wave caused by calving of the glacier into the lake). The real cause of the flood was Scenario 5 (earthquake-induced piping). In fact, Lake Safuna Alta was assessed as the lake with the highest potential for Scenario 5 of all of the assessed lakes. From this point of view, it is also quite important to compare the results within each scenario (see 3.3.2).

3.3.2 The most susceptible lake for each scenario

The results of the assessment of the potential for each scenario were ranked from the highest to the lowest potential for a GLOF (see Tab. 5). In general, the presented method reliably distinguishes between lakes which later produced GLOFs to those which did not. Detailed results for each scenario are described below.

Scenario 1: It can be clearly seen that the susceptibility to outburst floods of pre-flood conditions of lakes which have produced GLOFs by Scenario 1 reached the seven highest potentials (Fig. 7). Three conditions reached the maximal potential of 1.00. These were the conditions of Lake Artesoncocha, before it produced GLOFs in July and October 1951 and Lake Palcacocha before it produced a GLOF in 1941. Four other lakes which have already produced GLOFs reached a potential for Scenario 1 higher than 0.95. After that, a significant decrease in the reached potentials is evident and lakes which have yet to produce GLOFs are ranked.

The presented method works perfectly until the thirteenth position. After that there are two evident disharmonies – the Lake Safuna Alta 2002 event (14th position) and the Lake No. 513 2010 event (20th position). We have the following explanation for this phenomenon: Firstly, both of these events were caused by an extraordinary high-volume slope movement, which cannot be reliably identified or accurately predicted without detailed field glaciological and geological survey. Secondly, both of these lakes have a dam freeboard in the order of tens of meters, which would help to significantly limit the expected low- or middle-scale events and thus decrease the susceptibility for dam overtopping in the presented method. From another point of view, the large-scale fast slope movement can be characterised as a "quasi-random" event (see 4.3) and a GLOF following its potential impact on the affected lake may occur elsewhere, even from an ostensibly safe lake (e.g. Lake No. 513, which was generally considered as safe after the level of the artificial lake decreased by about 20 m, nevertheless a GLOF occurred in 2010; Carey, 2012).

Scenario 2: The presented method reliably identified the only event that involved Scenario 2 (Fig. 8). This was dam overtopping and subsequent dam failure of Lake Atizon Bajo following a flood wave from Lake Artizon Alto in 2012 (potential 0.996). Two other lakes have significantly large lake situated upstream in their catchment area, and thus have a nonzero potential for Scenario 2 (Churup and the upstream situated Lake Churupito; Auquiscocha and the upstream situated Lake Checquiacocha). Neither of these systems have produced a GLOF and this was confirmed by them reaching significantly lower potentials (0.574 and 0.553, respectively) in comparison with the Atizon cascade. On the other hand, the low number of the examined events of this scenario is a potential shortcoming, with the Artizon 2012 event being the only well-documented event of Scenario 2 (Scenario 4, respectively) from the Cordillera Blanca region.

Scenario 3: The results of the potential for dam failure following fast slope movement into the lake reliably identified the dam failures of Lake Palcacocha in 1941 (potential 0.559) and Lake Jancarurish in 1951 (potential 0.554; see Fig. 9). The remaining two dam failures of Lake Artesoncocha reached a substantially lower potential (0.259 and 0.225, respectively) than the potentials reached by lakes which have not produced GLOFs yet (Quitacocha, Checquiacocha). These lakes we interpret as being susceptible to dam failure following fast slope movement into the lake. It is important to realise that dam erodibility (a component of this scenario) is quite a complex issue, which is always estimated with a degree of uncertainty and approximation when the assessment is based on remotely sensed photos and DTMs (topographical maps) without any field survey. If we take this fact into the account then the provided results are quite representative.

Scenario 4: Our investigation showed that the only lake susceptible to Scenario 4 is Lake Artizon Bajo (its pre-flood condition, respectively) with a potential of 0.207 (Fig. 10). This lake produced a GLOF in this way in 2012. No other lake from the examined lakes is susceptible to this scenario (there are no lakes significant in size situated upstream of the assessed moraine-dammed lakes). The presented method reliably identifies the lake susceptible to outburst floods in this case. As in the case of Scenario 2, the low number of examined events (dam failures following this mechanism) has to be considered, with the Artizon 2012 event being the only well-documented event of Scenario 4 from the Cordillera Blanca region.

Scenario 5: Lake with a higher potential for Scenario 5 was also identified successfully (Fig. 11). The only case of this scenario from the examined events (piping of Lake Safuna Alta after a strong earthquake in 1970) reached the highest potential of 0.231, followed by the condition of Lake Palcacocha before the 1941 outburst with a potential of 0.217. Afterwards there was a significant decrease in potential, with the third position being occupied by the pre-flood condition of the Safuna Alta 2003 event as well as lakes Churupito and Mullaca.

3.3.3 Lakes susceptible to outburst floods

Based on a comparison of the results obtained from the assessment of susceptibility of ten pre-flood conditions of lakes which have already produced GLOFs and ten conditions of lakes which have yet to produce GLOFs, we recommend interpreting “lakes susceptible to the outburst flood” as lakes which reach more than 0.9 in Scenario 1, more than 0.5 in Scenario 3; or more than 0.2 in Scenario 5. In the case of Scenarios 2 and 4, we recommend using the above mentioned values depending on the most likely scenario of a GLOF originating from an upstream situated lake. The relatively low number of examined events should also be taken into consideration.

4 Discussion

4.1 Method construction, decision trees and calculations

In order to provide an easily repeatable and reproducible methodological concept for assessing the susceptibility of a greater number of glacial lakes to outburst floods without the need for field survey (based on remotely sensed data, DTMs and / or topographical maps), it was necessary to provide a clear and instructive guide (represented by decision trees), where all of the thresholds are defined and thus the room for doubt during assessment is limited as much as possible. Therefore, it is clear that some simplifications needed to be done. These simplifications are connected especially to the schematic description of the GLOF mechanisms (scenarios); on the other hand, all of these scenarios have previously been described from the study area and they are not artificial. Also, several of the equations used in the calculations are schematic or simplified (e.g. Eqs. (10, 11, 14)) due in particular to the limited demand on input data (assumption of repeatability and reproducibility). In addition some thresholds needed to be estimated artificially (e.g. constant 0.05 in Eq. (8)). In these cases, more detailed investigation for more precise estimation of these thresholds should be performed in the future (see the recommendation for the future research in section 5). Manual assessment of certain characteristics such as dam type is also needed in the presented method (see also method disadvantages in subsection 4.4).

4.2 Interpretation of results

It is highly important not to misinterpret the obtained results with regard to the character of the presented method. Therefore, we would like to emphasize that the presented method provides information about the susceptibility of a particular glacial lake to outburst floods. Potentials for five different scenarios of GLOFs, which have been previously recorded in the studied region, are assessed. On the other hand, the presented method does not reflect any other possible GLOF scenario (e.g. dam failure following melting of buried ice reported from mountain ranges of Central Asia; Ives et al., 2010; Richardson and Reynolds, 2000b). The presented method also does not take into account the magnitude of potential outburst floods (as well as e.g. the volume of potential fast slope movement into the lake), or downstream impacts (downstream hazard assessment).

4.3 Potential sources of errors

It is not possible to exactly predict the behaviour of the complex Earth system with the current state of knowledge and analogically the occurrence of GLOFs cannot be exactly predicted because this question is also highly complex. We are able to modify the spatial component or time component of the assessment but we are not able to refine both of these components simultaneously. This fact is connected with the so called “quasi-randomness” of the triggering events, e.g. spatio-temporal occurrence and magnitude of fast slope movements, spatio-temporal occurrence and magnitude of earthquakes and occurrence of extreme weather (O'Connor et al., 2001). The quasi-randomness and complexity of GLOF occurrence thus limit the reliability of each method, including the presented one, and represent a potential source of errors. On the other hand, modification of all of the existing approaches and particular methods for use on a regional scale is an attractive scientific challenge. Beside the quasi-randomness and partial unpredictability of the complex Earth system behaviour, potential sources of errors are especially connected to the acquisition and interpretation of input data. Therefore, we recommend using comprehensive and uniform input data, if possible.

4.4 Advantages and disadvantages of the presented method

In comparison with existing methods for assessing susceptibility of glacial lakes to outburst floods, we feel that the main advantages of the presented method are as follows:

(a) repeatability, which allows both retrograde, present and also near-future assessment of the susceptibility of glacial lakes to outburst floods and their evolution in time;

(b) reproducibility, which allows different observers to gain equal results using the same input data;

(c) the principle of multiple results, which allows the most likely GLOF scenario for each lake to be identified and allows characteristics which do not play a role in a specific case to be omitted (scenarios, decision trees).

On the other hand, the presented method also has certain disadvantages, which mainly result from the type of construction of the method (see 4.1). These are:

(a) a compromise between the demands on input data on the one hand and repeatability, reproducibility and the relevance of the obtained results on the other hand;

(b) the need for a partial manual assessment (especially for qualitative discrete characteristics such as a distinction between different types of dams, identification of evidence of piping or type of remedial work)

(c) time-consuming acquisition of input data for a higher number of assessed lakes (17 characteristics needed for each lake).

5 Conclusions and future work

Glacial lake outburst floods (GLOFs) are highly important fluvial as well as geomorphological processes, which represent a significant threat to the inhabitants of the Cordillera Blanca region, Peru. In these days of global climate change and subsequent glacier retreat, the threat of GLOFs is actually increasing. Reliable identification of the threat and assessment of the susceptibility of glacial lakes to outburst floods is a necessary step in risk management and is a basic precondition for the application of effective mitigation tools. In this paper, a new and easily repeatable method for assessing the susceptibility of glacial lakes to outburst floods within the Cordillera Blanca region is presented. In contrast with existing methods, this regionally-focused method is based on an assessment of five separate potentials for five different GLOF scenarios, which have been recorded in the studied region. Assessment of pre-GLOF conditions of lakes which have produced GLOFs in the past and a comparison of these results with an assessment of lakes which have not produced GLOFs yet showed that this method has great potential for identifying the most likely GLOF scenario for a particular lake and also for identifying the most susceptible lake(s) within a group of lakes for each scenario. A distinction between lakes which have already produced GLOFs from those which have not was successful in all five scenarios. We believe that the presented method will serve as an integrated methodological concept for repeated assessment of the susceptibility of glacial lakes to outburst floods within the Cordillera Blanca region.

For future work we recommend especially:

(a) a more detailed investigation for more precise specification of thresholds and calculations, based on an analysis of previous GLOFs as well as a field survey (geophysical measurements for estimating the stability of moraine slopes, measurements elucidating the internal structure of moraine dams, …);

(b) extension of the method for all types of high-mountain lakes (especially for the landslide-dammed lakes which have reached significant volumes in the studied region);

(c) an inventory and semi-automatic assessment of the susceptibility of lakes of a significant size within the Cordillera Blanca region to outburst floods, based on the usage of GIS;

(d) flood modelling for the lakes with the highest susceptibility to outburst floods, delimitation of potentially affected areas downstream;

(e) implementation of effective outburst floods hazard (risk) management tools (both active and passive mitigation measures).

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Table 1. Scenarios of GLOFs and their components.

Scenario	Description	Components	Number of assessed characteristics
Scenario 1	Dam overtopping following fast slope movement into the lake	Potential for fast slope movement into the lake	6
		Potential for dam overtopping by displacement wave	2
Scenario 2	Dam overtopping following the flood wave originating in a lake situated upstream	Potential for flood wave from a lake situated upstream	17*
		Retention potential of assessed lake	4
Scenario 3	Dam failure resulting from fast slope movement into the lake	Potential for fast slope movement into the lake	6
		Potential for dam overtopping by displacement wave	2
		Dam erodibility for Scenario 3	4
Scenario 4	Dam failure following the flood wave originating in a lake situated upstream	Potential for flood wave from a lake situated upstream	17*
		Retention potential of assessed lake	4
		Dam erodibility for Scenario 4	6
Scenario 5	Dam failure following strong earthquake	Potential for strong earthquake	0[#]
		Dam instability	5

* - complete procedure for assessing the susceptibility to the outburst flood of a lake situated upstream.

[#] - no input data needed (see 2.3.5).

Table 2. Individually assessed characteristics (input data) used in the presented method.

Characteristic	Use in scenario(s)	Definition	Acronym [unit]	Threshold	References(s)
Dam characteristics:					
Dam type	S3, S4, S5	Type of material, which predominantly forms the lake dam	- [Qualitative discrete variable]	moraine dam x bedrock dam	e.g. Huggel et al. 2004; Mergili and Schneider, 2011
Dam freeboard	S1, S2, S3, S4	Vertical distance between the lake level and the lowest point on the dam crest	D_f = [m]	$D_f = 0$ m – lakes with surface outflow; $D_f > 0$m – continuous variable	e.g. Clague and Evans, 2000; Grabs and Hanisch, 1993; Huggel et al. 2004; Wang et al., 2008
Dam width	S5	Horizontal distance between the dam toe and the lake surface	D_w =[m]	None (continuous variable)	Huggel et al., 2004; McKillop and Clague, 2007a
Dam height	S5	Vertical distance between the dam toe and the lowest point on the moraine crest	D_h =[m]	None (continuous variable)	Huggel et al., 2004; McKillop and Clague, 2007a
Maximal slope of distal face of the dam	S3, S4	Maximal slope of distal face of the dam measured in the surface outflow channel, where possible	S_{DFDmax} = [°]	None (continuous variable)	This study
Piping	S5	Evidence for spring(s) on the distal face of the dam body	- [Qualitative discrete variable]	yes x no	Clague and Evans, 2000; Grabs and Hanisch, 1993
Piping gradient	S5	Mean slope between the piping spring and the nearest lakeshore	γ = [°]	None (continuous variable)	This study

Remedial work	S3, S4	Application of remedial works on the lake dam and their type	- [Qualitative discrete variable]	concrete outflow x artificial dam x tunnel	This study
Lake characteristics:					
Lake area	S1, S2, S3, S4	Lake surface area	A = [m^2]	None (continuous variable)	Chen et al., 1999; McKillop and Clague, 2007a
Lake perimeter	S2, S4	Lake surface perimeter	L_{lac} = [m]	None (continuous variable)	This study
Maximal lake width	S1, S3	Shortest (linear) connectin line between the right and left banks at the widest part of the lake (perpendicular to the lake length, which is defined as the shortest connecting line between the most distant opposite lake shores)	L_{w} = [m]	None (continuous variable)	This study
Lake surrounding characteristics:					
Distance between lake and glacier	S1, S3	Shortest distance between the assessed lake (its lakeshore) and the closest glacier situated above the lake	D_{is} = [m]	D_{is} = 0 m – direct contact between the lake and glacier; D_{is} > 0 m – continuous variable	e.g. Grabs and Hanisch, 1993; Yamada, 1993

Width of calving front	S1, S3	Horizontal distance between the left and right margins of a calving glacier	C_{lw} = [m]	None (continuous variable)	McKillop and Clague, 2007a; Richardson and Reynolds, 2000a
Mean slope between lake and glacier	S1, S3	Mean slope between the lake and glacier measured on the shortest connecting line between the glacier terminus and the lakeshore	S_{LG} = [°]	None (continuous variable)	Wang et al., 2011
Mean slope of last 500 m of glacier tongue	S1, S3	Mean slope of the last 500 m of the glacier tongue situated above the assessed lake and which is the closest to the lakeshore	S_{G500} = [°]	None (continuous variable)	Grabs and Hanisch, 1993; Wang et al., 2011
Maximal slope of moraine surrounding the lake	S1, S3	Maximal slope of the moraine facing the assessed lake and measured from the lakeshore to the moraine crest	S_{Mmax} = [°]	None (continuous variable)	This study
Mean slope of lake surrounding	S2, S4	Mean slope of slopes facing the assessed lake	α = [°]	None (continuous variable)	This study

S1: dam overtopping resulting from a fast slope movement into the lake; S2: dam overtopping following a flood wave originating in a lake situated upstream; S3: dam failure resulting from fast slope movement into the lake; S4: dam failure following a flood wave originating in a lake situated upstream; S5: dam failure following a strong earthquake.

Table 3. List of examined lakes (historical GLOFs).

Lake	Valley	Date of GLOF	Lake type	Probable scenario	Reference
Artesoncocha (7/1951)	Parón	16th - 17th July 1951	MDL	Dam failure following icefall into the lake	Ghiglino and Spann, 1951; Lliboutry et al., 1977
Artesoncocha (10/1951)	Parón	28th October 1951	MDL	Dam failure following icefall into the lake	Torres and Brottger, 1951 Lliboutry et al., 1977
Artizon Alto	Artizon / Santa Cruz	8th February 2012	BDL	Dam overtopping following a landslide of lateral moraine into the lake	Emmer et al., 2014
Artizon Bajo	Artizon / Santa Cruz	8th February 2012	MDL	Dam failure following a flood wave from a lake situated upstream	Emmer et al., 2014
Jancarurish	Los Cedros	20th October 1950	MDL	Dam failure following icefall into the lake	Lliboutry et al., 1977
Lake No. 513	Chucchun	11th April 2010	BDL	Dam overtopping following ice / rock fall into the lake	Carey et al., 2012; Klimeš et al., 2014
Palcacocha (1941)	Cojup	13th December 1941	MDL	Dam failure following icefall into the lake	Oppenheim, 1946
Palcacocha (2003)	Cojup	19th March 2003	MDL	Dam overtopping following a landslide of lateral moraine into the lake	Vilímek et al., 2005
Safuna Alta (1970)	Tayapampa /Collota	31st May 1970	MDL	Dam failure caused by an earthquake	Lliboutry et al., 1977
Safuna Alta (2002)	Tayapampa /Collota	22nd April 2002	MDL	Dam overtopping following a rockslide / rockfall into the lake	Hubbard et al., 2005

BDL: bedrock-dammed lake; MDL: moraine-dammed lake

Table 4. Pre-GLOF condition (susceptibility to outburst floods) of lakes assessed by the presented method (**Bold** – the highest potential for a particular lake; *italicized* – the actual cause).

Lake (condition)	Recorded GLOF trigger and mechanism	Potential for dam overtopping as a result of:		Potential for dam failure as a result of:		
		fast slope movement into the lake	Flood wave from a lake situated upstream	fast slope movement into the lake	Flood wave from a lake situated upstream	strong earthquake
Artesoncocha (7/1951)	Dam failure following icefall into the lake	***1.000*** (calving)	0.000	***0.259***	0.000	0.025
Artesoncocha (10/1951)	Dam failure following icefall into the lake	***1.000*** (calving)	0.000	***0.225***	0.000	0.019
Artizon Alto	Landslide of moraine / dam overtopping	***0.996*** (landslide)	0.000	0.000	0.000	0.000
Artizon Bajo	Flood wave from a lake situated upstream /dam failure	0.985 (landslide)	***0.996***	0.205	***0.207***	0.026
Jancarurish	Icefall / dam failure	***0.983*** (calving)	0.000	***0.554***	0.000	0.135
Lake No. 513	Icefall / dam overtopping	***0.378*** (icefall)	0.000	0.000	0.000	0.000
Palcacocha (1941)	Icefall / dam failure	***1.000*** (calving)	0.000	***0.559***	0.000	0.217
Palcacocha (2003)	Landslide of moraine / dam overtopping	***0.961*** (calving)	0.000	0.000	0.000	0.026

Safuna Alta (1970)	Dam failure following strong earthquake	**0.604** (calving)	0.000	0.279	0.000	*0.231*
Safuna Alta (2002)	Landslide of moraine / dam overtopping	***0.589*** (landslide)	0.000	0.261	0.000	0.147

Table 5. Results of the assessment of the susceptibility of the examined lakes (and pre-floods conditions) ranked from the highest to the lowest for each scenario (**Bold** – non-zero results; please note that the zero results are listed alphabetically).

Rank	Scenario 1		Scenario 2		Scenario 3		Scenario 4		Scenario 5	
	Lake (condition)	Result	Lake (condition)	Result	Lake (condition)	Result	Lake (condition)	Result	Lake (condition)	Result
1.	Artesoncocha (7/1951)	**1.000**	Artizon Bajo	**0.996**	Palcacocha (1941)	**0.559**	Artizon Bajo	**0.207**	Safuna Alta (1970)	**0.231**
2.	Artesoncocha (10/1951)	**1.000**	Auquiscocha	**0.574**	Jancarurish	**0.554**	Artesoncocha (7/1951)	0.000	Palcacocha (1941)	**0.217**
3.	Palcacocha (1941)	**1.000**	Churup	**0.553**	Safuna Alta (1970)	**0.279**	Artesoncocha (10/1951)	0.000	Safuna Alta (2003)	**0.147**
4.	Artizon Alto	**0.996**	Artesoncocha (7/1951)	0.000	Safuna Alta (2002)	**0.261**	Artizon Alto	0.000	Churupito	**0.147**
5.	Artizon Bajo	**0.985**	Artesoncocha (10/1951)	0.000	Quitacocha	**0.261**	Auquiscocha	0.000	Mullaca	**0.147**
6.	Jancarurish	**0.983**	Artizon Alto	0.000	Artesoncocha (7/1951)	**0.259**	Checquiacocha	0.000	Jancarurish	**0.135**
7.	Palcacocha (2003)	**0.961**	Checquiacocha	0.000	Checquiacocha	**0.243**	Churup	0.000	Quitacocha	**0.122**
8.	Rajucolta	**0.668**	Churupito	0.000	Artesoncocha (10/1951)	**0.225**	Churupito	0.000	Llaca	**0.072**
9.	Llaca	**0.651**	Ishinca	0.000	Churupito	**0.225**	Ishinca	0.000	Ishinca	**0.067**
10.	Tararhua	**0.643**	Jancarurish	0.000	Artizon Bajo	**0.205**	Jancarurish	0.000	Checquiacocha	**0.034**
11.	Quitacocha	**0.624**	Lake No. 513	0.000	Tararhua	**0.089**	Lake No. 513	0.000	Artizon Bajo	**0.026**
12.	Ishinca	**0.612**	Llaca	0.000	Artizon Alto	0.000	Llaca	0.000	Palcacocha (2003)	**0.026**
13.	Safuna Alta (1970)	**0.604**	Mullaca	0.000	Auquiscocha	0.000	Mullaca	0.000	Artesoncocha (7/1951)	**0.025**

14.	Safuna Alta (2002)	**0.589**	Palcacocha (1941)	0.000	Churup	0.000	Palcacocha (1941)	0.000	Rajucolta	**0.025**
15.	Checquiacocha	**0.574**	Palcacocha (2003)	0.000	Ishinca	0.000	Palcacocha (2003)	0.000	Artesoncocha (10/1951)	**0.019**
16.	Churupito	**0.553**	Quitacocha	0.000	Lake No. 513	0.000	Quitacocha	0.000	Tararhua	**0.016**
17.	Auquiscocha	**0.500**	Rajucolta	0.000	Llaca	0.000	Rajucolta	0.000	Artizon Alto	0.000
18.	Mullaca	**0.48**	Safuna Alta (1970)	0.000	Mullaca	0.000	Safuna Alta (1970)	0.000	Auquiscocha	0.000
19.	Churup	**0.423**	Safuna Alta (2002)	0.000	Palcacocha (2003)	0.000	Safuna Alta (2002)	0.000	Churup	0.000
20.	Lake No. 513	**0.378**	Tararhua	0.000	Rajucolta	0.000	Tararhua	0.000	Lake No. 513	0.000

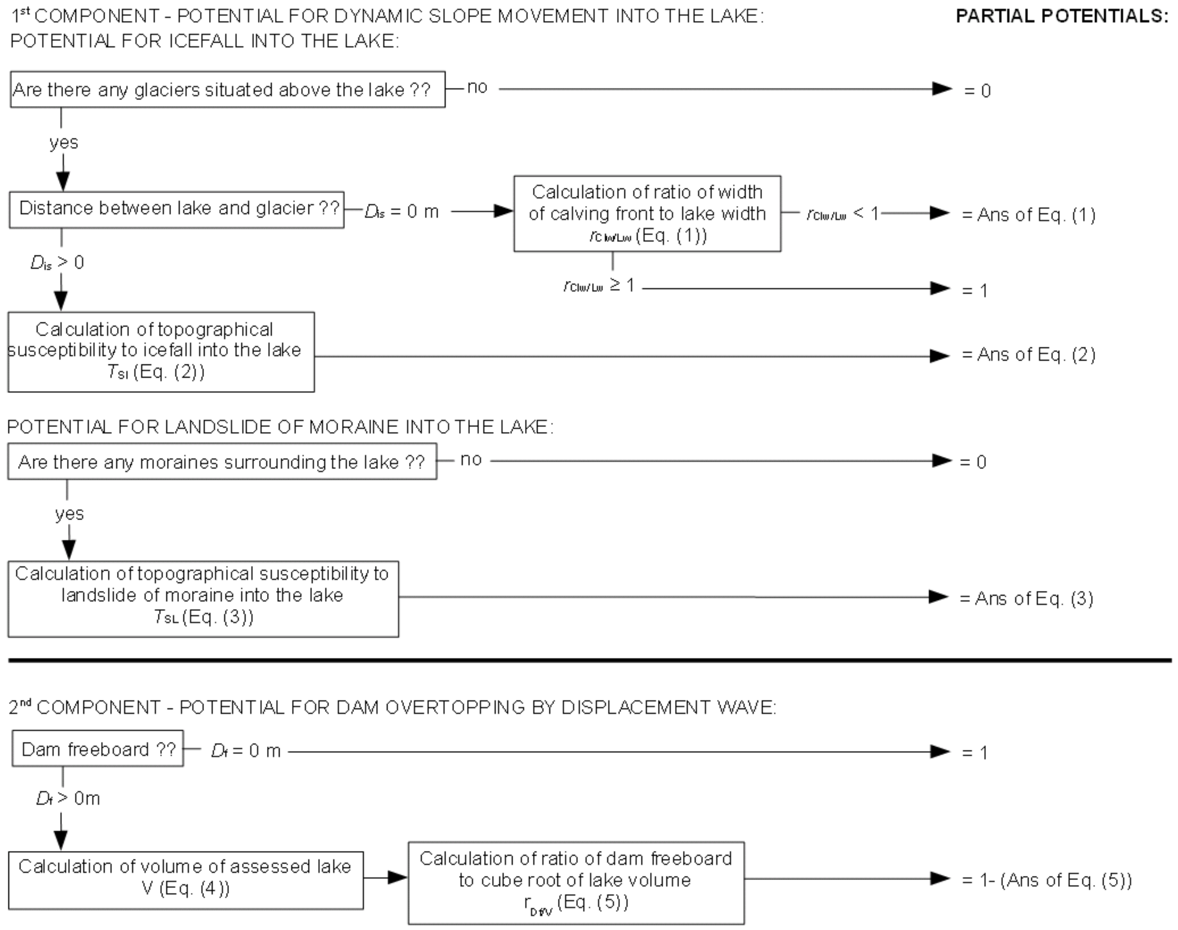

Figure 1. Decision tree for assessing the potential for dam overtopping resulting from a fast slope movement into the lake. The overall potential is derived as a product of the highest partial potentials of the first and second components.

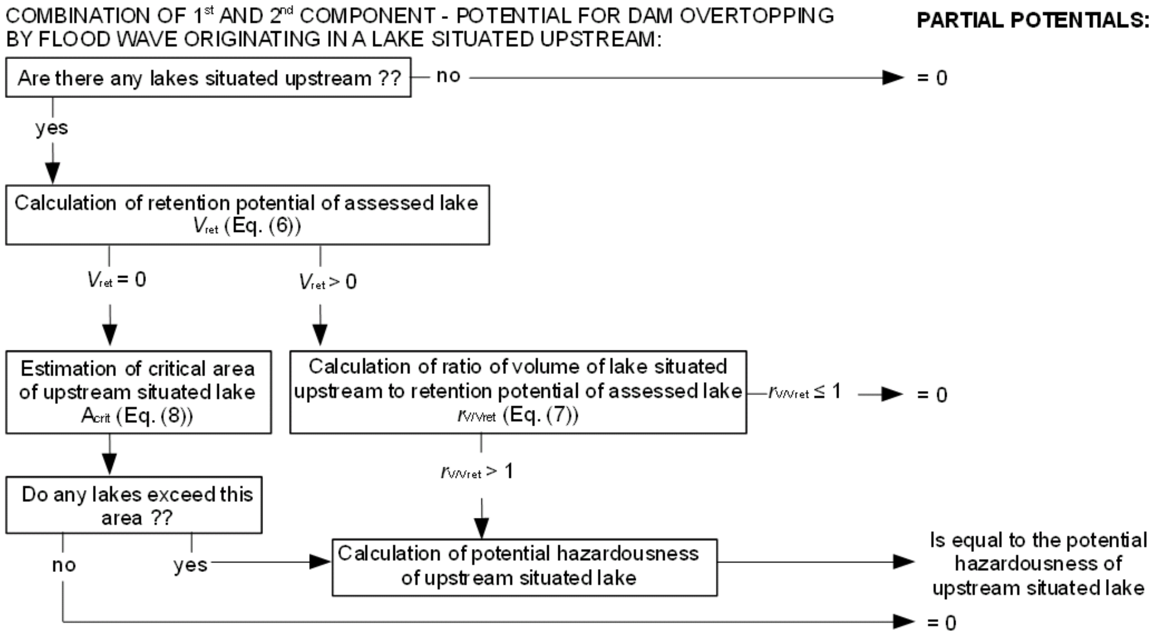

Figure 2. Decision tree for assessing the potential for dam overtopping following a flood wave originating in a lake situated upstream.

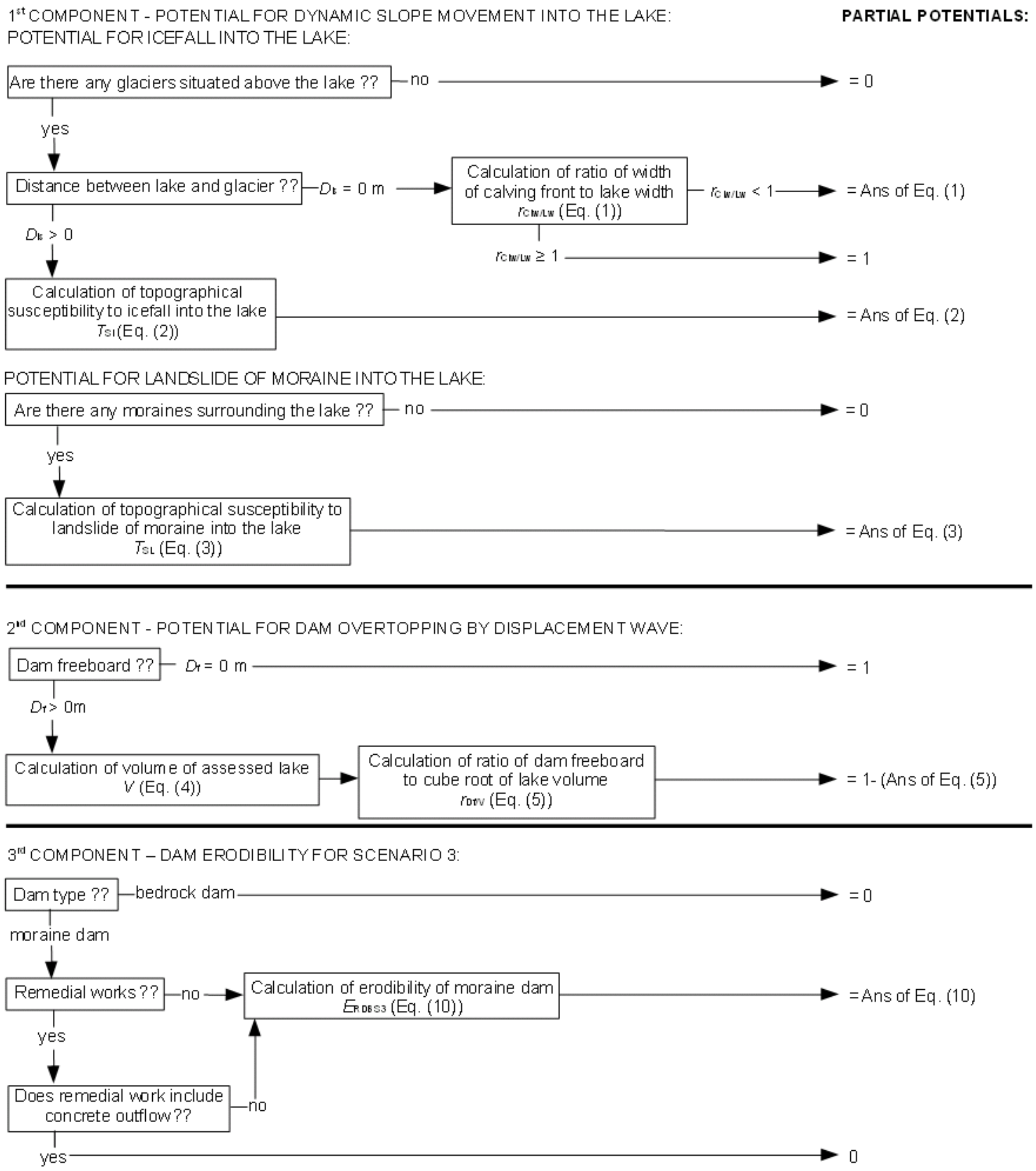

Figure 3. Decision tree for assessing the potential for dam failure resulting from a fast slope movement into the lake. The overall potential is derived as a product of three partial components.

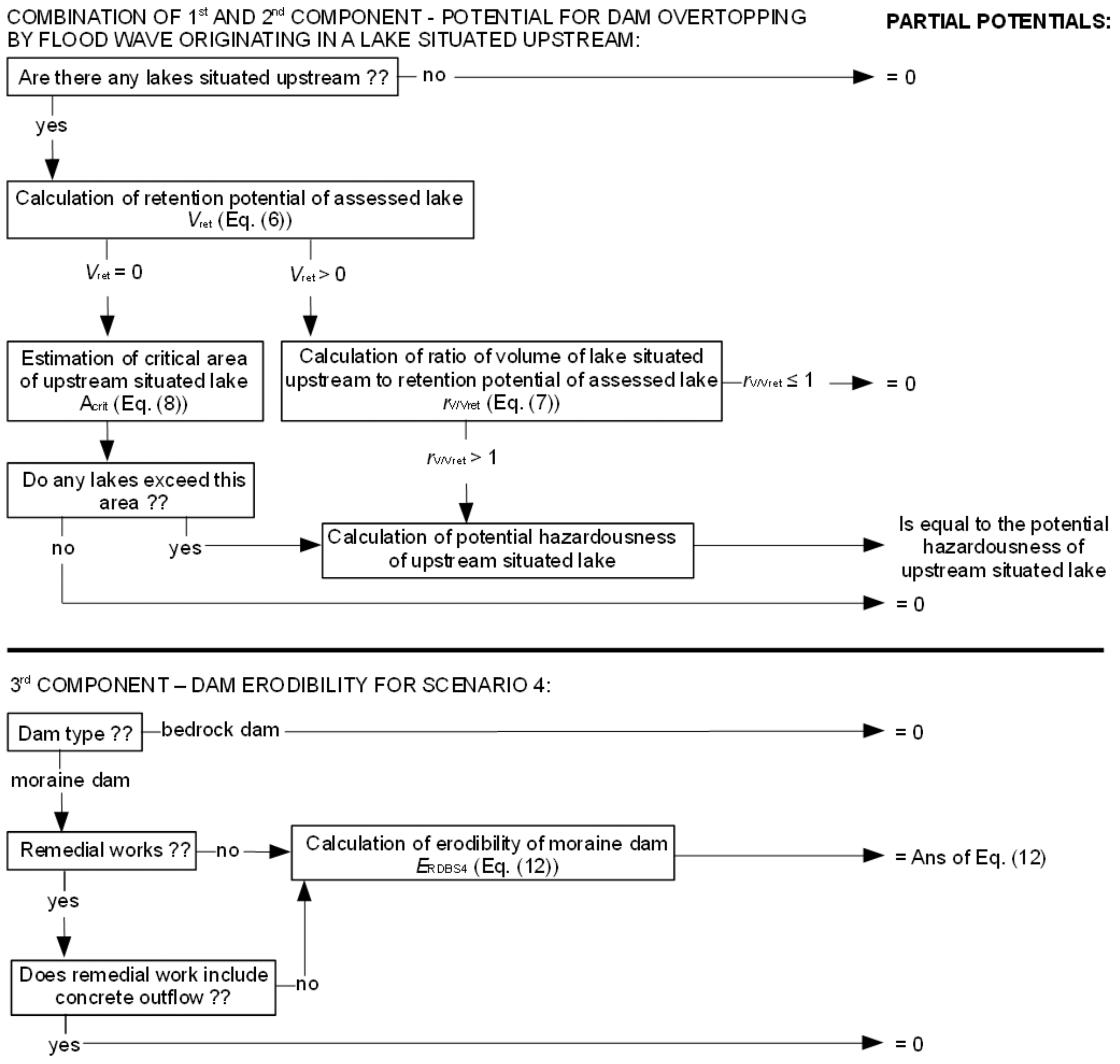

Figure 4. Decision tree for assessing the potential for dam failure following a flood wave originating in a lake situated upstream. The overall potential is derived as a product of three partial components.

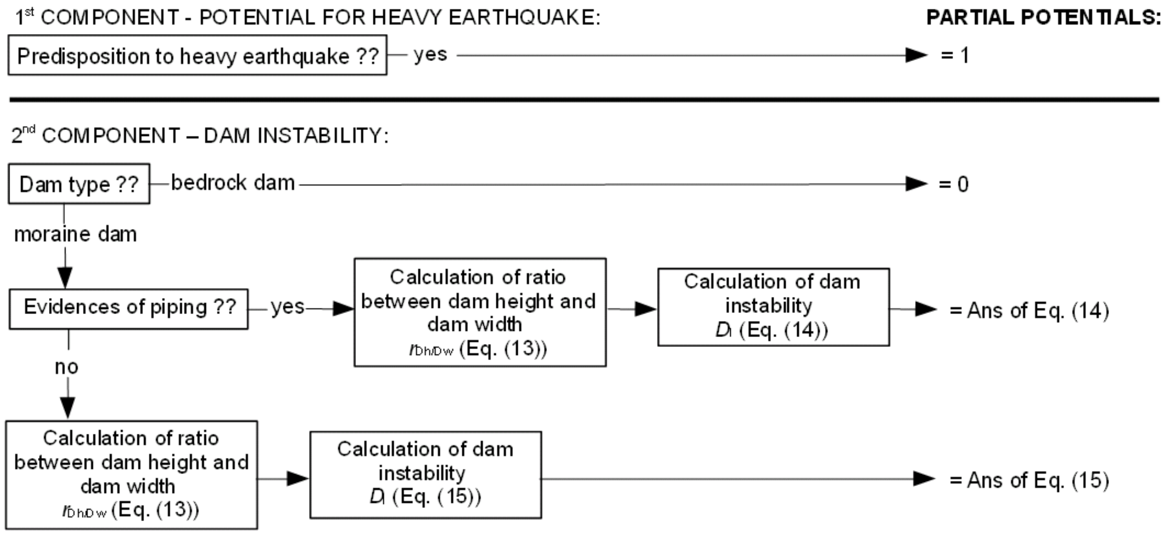

Figure 5. Decision tree for assessing the potential for dam failure following a strong earthquake.

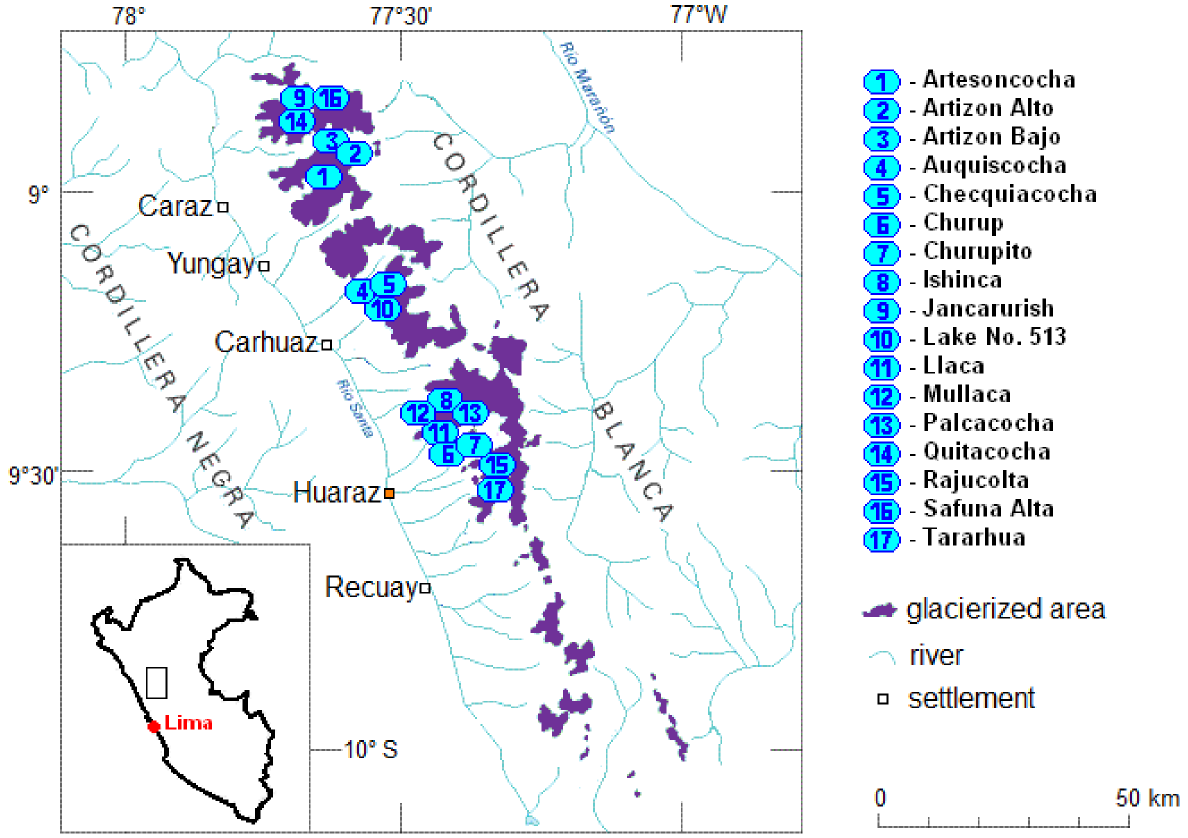

Figure 6. Localization of studied lakes (base map modified according to: USGS).

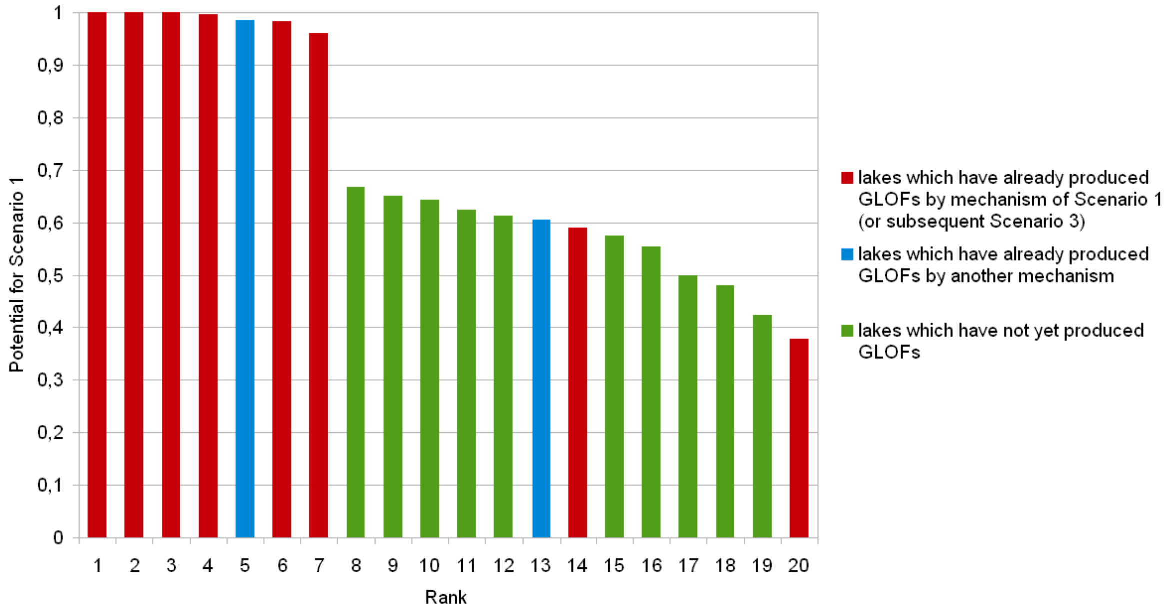

Figure 7. Assessed lakes and their potential for Scenario 1 ranked from the highest to the lowest. The results for particular lakes are listed in Table 6.

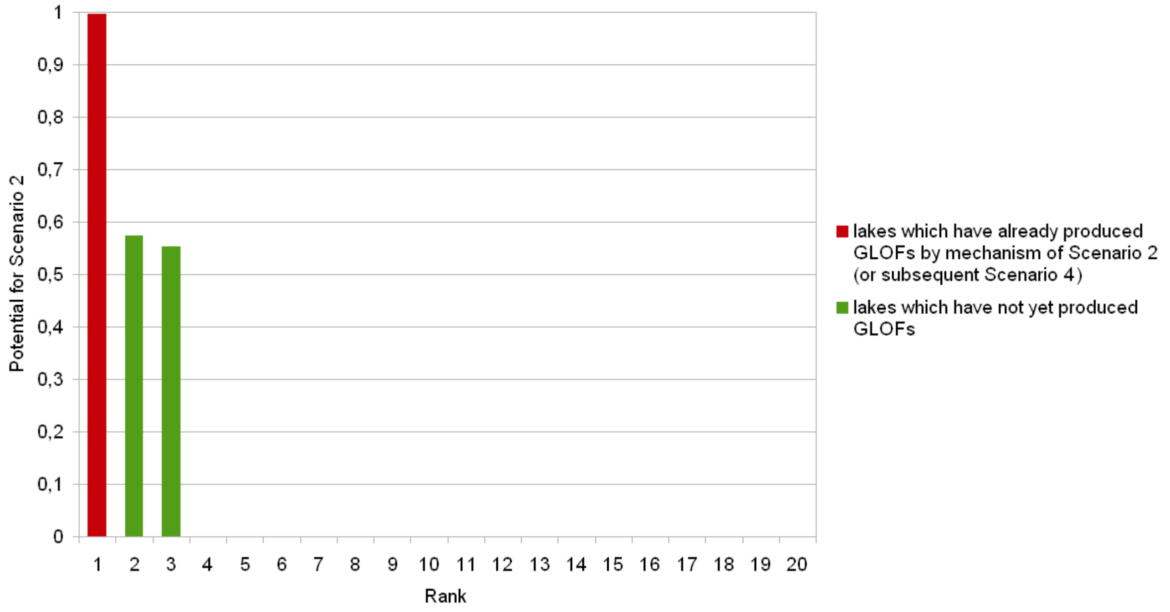

Figure 8. Assessed lakes and their potential for Scenario 2 ranked from the highest to the lowest (please note that the empty columns represent lakes with a zero potential for this scenario; the results for particular lakes are listed in Table 6.).

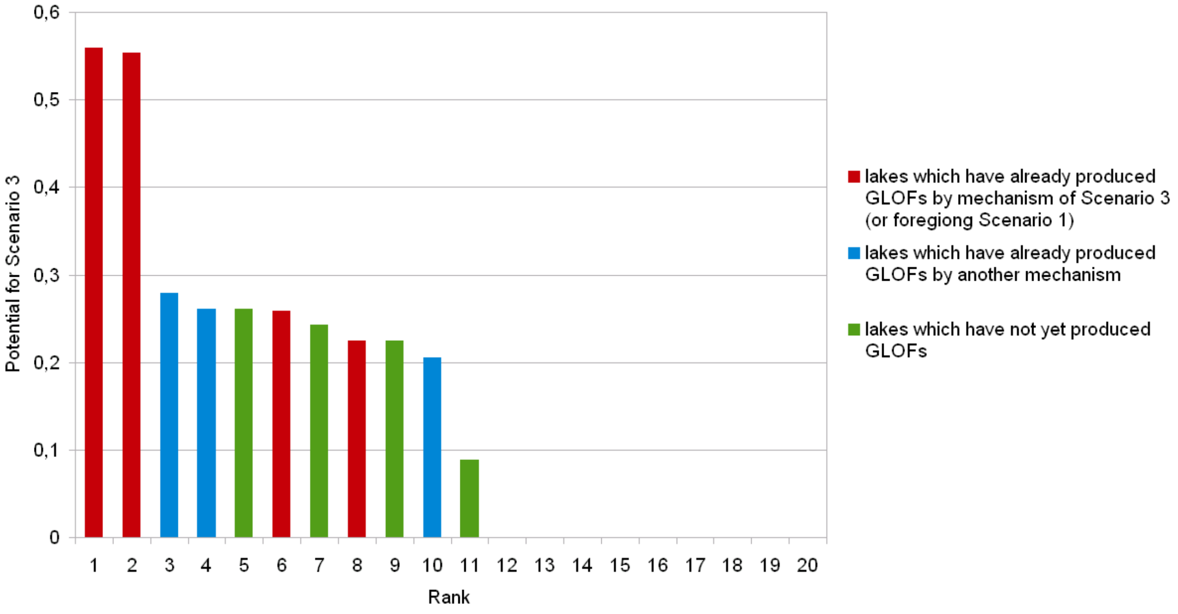

Figure 9. Assessed lakes and their potential for Scenario 3 ranked from the highest to the lowest (please note that the empty columns represent lakes with a zero potential for this scenario; the results for particular lakes are listed in Table 6.).

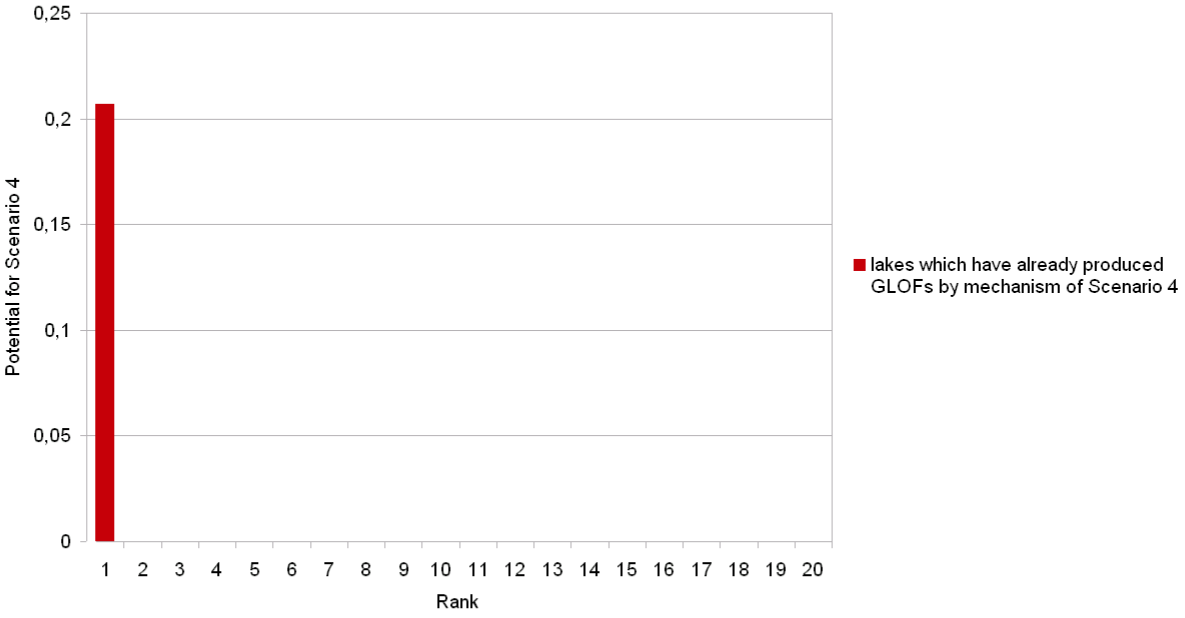

Figure 10. Assessed lakes and their potential for Scenario 4 ranked from the highest to the lowest (please note that empty columns represent lakes with a zero potential for this scenario; the results for particular lakes are listed in Table 6.).

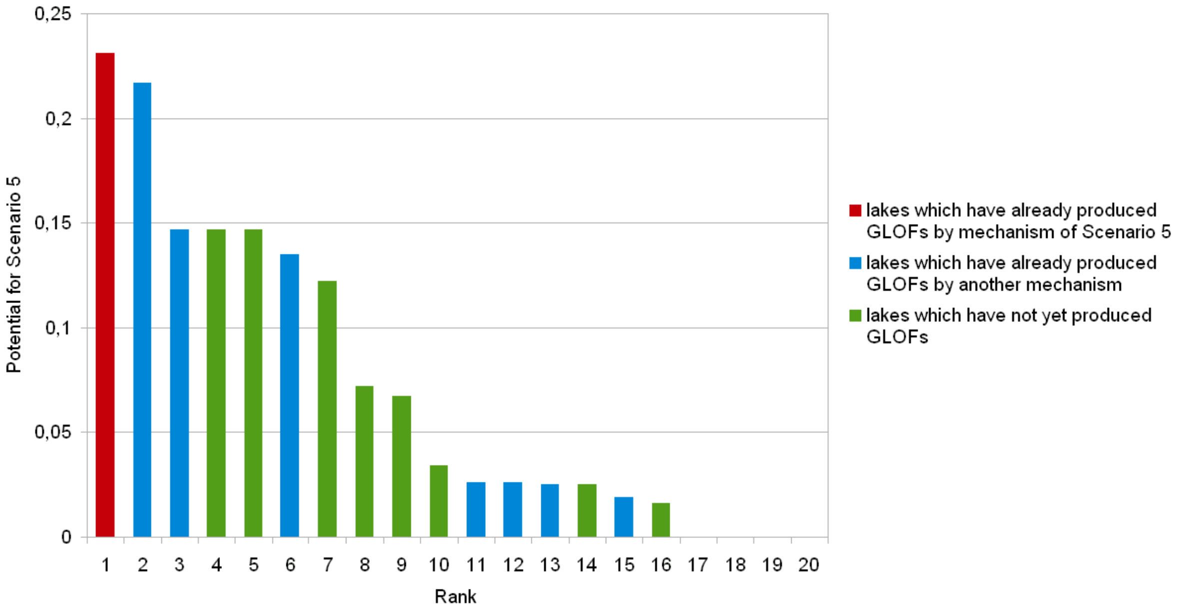

Figure 11. Assessed lakes and their potential for Scenario 5 ranked from the highest to the lowest (please note that the empty columns represent lakes with a zero potential for this scenario; the results for particular lakes are listed in Table 6.).