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Review Article: Lake and breach hazard assessment for moraine-dammed lakes: an example from the Cordillera Blanca (Peru)

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Abstract. Glacial lake outburst floods (GLOFs) and related debris flows represent a significant threat in high mountainous areas across the globe. It is necessary to quantify this threat so as to mitigate their catastrophic effects. Complete GLOF hazard assessment incorporates two phases: the probability of water release from a given glacial lake is estimated through lake and breach hazard assessment while the endangered areas are identified during downstream hazard assessment. This paper outlines a number of methods of lake and breach hazard assessment, which can be grouped into three categories: qualitative, of which we outline eight; semi-quantitative, of which we outline two; and quantitative, of which we outline three. It is considered that five groups of critical parameters are essential for an accurate regionally focused hazard assessment method for moraine-dammed lakes in the Cordillera Blanca. These comprise the possibility of dynamic slope movements into the lake, the possibility of a flood wave from a lake situated upstream, the possibility of dam rupture following a large earthquake, the size of the dam freeboard (or ratio of dam freeboard), and a distinction between natural dams and those with remedial work. It is shown that none of the summarised methods uses all these criteria with, at most, three of the five considered by the outlined methods. A number of these methods were used on six selected moraine-dammed lakes in the Cordillera Blanca: lakes Quitacocha, Checquiacocha, Palcacocha, Llaca, Rajucolta, and Tararhua. The results have been compared and show that each method has certain advantages and disadvantages when used in this region. These methods demonstrate that the most hazardous lake is Lake Palcacocha.

1 Introduction

The term glacial lake outburst flood (GLOF) is used to describe the sudden release of water from a glacial lake (e.g. Benn and Evans, 1998; Clague and Evans, 2000). GLOFs have been studied in high mountainous areas across the globe, including the Himalayas (Kattelmann and Watanabe, 1997; Yamada, 1998; Quincey et al., 2007; Bajracharya et al., 2007), Karakoram (Hewitt, 1982), Hindu Kush (Iturrizaga, 2005; Ives et al., 2010), Tian Shan (Narama et al., 2010; Bolch et al., 2011; Engel et al. 2012), Pamir (Mergili and Schneider, 2011), Caucasus Mts. (Petrakov et al., 2007), Peruvian Andes (Reynolds, 2003; Vilímek et al., 2005a; Carey et al., 2012), Patagonia (Harrison et al., 2006; Dussaillant et al., 2009), Cascade Range (O'Connor et al., 2001), and British Columbia (Clague and Evans, 2000; Kershaw et al., 2005), as well as in the European Alps (Haeberli et al., 2001; Huggel et al., 2002) and Scandinavia (Breien et al., 2008).

GLOFs are characterised by a high transport and erosion potential (Cenderelli and Wohl, 2001; Breien et al., 2008) and, therefore, may convert rapidly into debris flows (O'Connor et al., 2001) with densities of about $1.5\,t\,m^{-3}$ (Yamada, 1998). The maximal discharge may exceed $10^4\,m^3\,s^{-1}$ (Costa and Schuster, 1988), while volume of the transported material may exceed millions of cubic meters (Evans, 2002; Hubbard et al., 2005). GLOFs most commonly result from dynamic slope movements into the lake such as icefalls, rockfalls, or landslides (e.g. Costa and Schuster, 1988; Jiang et al., 2004; Awal et al., 2010). There are also other triggers including earthquakes (Lliboutry et al., 1977; Clague and Evans, 2000), intense rainfall/snowmelt (Yamada, 1998), the melting of buried moraine ice cores

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(Richardson and Reynolds, 2000b), the blockage of underground outflow channels (O'Connor et al., 2001; Janský et al., 2006), and the downstream propagation of a flood wave (Vilímek et al., 2005b). It is also possible for there to be no obvious dynamic cause, a phenomenon termed "dam self-destruction" (Yamada, 1998). The likelihood of these various triggers, as well as the stability of moraine dam, has to be included in a precise hazard assessment (Richardson and Reynolds, 2000a; Hegglin and Huggel, 2008).

It is clear that GLOFs and related debris flows are significant geomorphic processes that represent a considerable threat to the inhabitants of high mountainous areas. These processes need to be studied thoroughly so as to mitigate their catastrophic effects or, ideally, to prevent them altogether (Silva and Caceres, 1995). It is, therefore, necessary to identify the potentially hazardous lakes and model flood scenarios so as to demarcate the endangered areas (Cenderelli and Wohl, 2001; Worni et al., 2012). The aim of this paper is to outline methods of lake and breach hazard assessment from moraine-dammed lakes and then to apply a number of these to six selected moraine-dammed lakes in the Cordillera Blanca of Peru. It is then possible to discuss the suitability of each method in relation to the regional specifics of this mountain range.

2 Methodology

The potential hazard associated with six moraine-dammed lakes is assessed in this study: these are the lakes of Quitacocha, Checquiacocha, Palcacocha, Llaca, Rajucolta, and Tararhua. They are all located within the basin of the Rio Santa, which ultimately drains into the Pacific Ocean (Fig. 1). These lakes were chosen for two reasons. First, they offer a range of divergent characteristics, which is important in order to identify differences between the various methods – three have natural dams (Quitacocha, Checquiacocha, and Tararhua) whereas three have dams with remedial works; some have a surface outflow (Checquiacocha and Tararhua) whereas others do not; some are in direct contact with a glacier (Palcacocha, Rajucolta and Llaca) whereas others are not. Second, the required data were readily available, from both remotely sensed imagery and fieldwork undertaken from May to July 2012 (at lakes Palcacocha and Llaca). The spaceborne and aerial images were used to obtain spatial information such as the distance between lake and glacier, the area of mother glacier, the amount of glacier shrinkage, and the identification of surface outflow. We also used published and unpublished reports from the archives of the Instituto Nacional de Recursos Naturales–Autoridad Nacional del Agua in Huaraz and the Instituto Geológico Minero y Metalúrgico of Peru in Lima. These data sources were used to obtain specific information such as the occurrence of piping through the moraine dam and bathymetric measurements. Table 1 presents a complete list of input data.

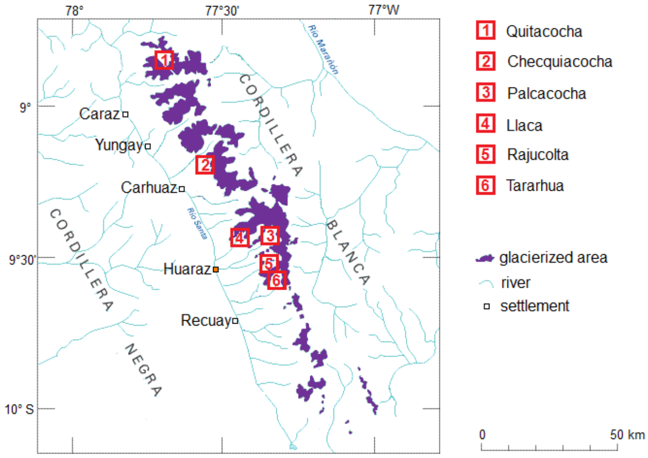

Fig. 1. The location of the selected lakes within the catchment of the Rio Santa in the Cordillera Blanca (base map: pubs.usgs.gov).

From the outlined methods we have used five of the qualitative methods to assess the six lakes listed previously. The potential hazard was defined by the number of negative parameters (parameters with a negative impact on the stability of a particular lake). The arithmetic mean of these results has been calculated. It is not possible to define which parameters are more important and, therefore, all carry the same weight. However, as certain parameters are repeated (e.g. distance between lake and glacier or contact with glacier), this clearly places greater weight on those stability parameters used by the greatest number of researchers. It was not possible to consider the stability parameter relating to the area of the mother glacier from the method presented by Wang et al. (2008) because no critical value is given for this parameter. The qualitative methods presented by Zapata (2002), Huggel et al. (2004), and Hegglin and Huggel (2008) were not considered because certain necessary critical values are not given and, therefore, the subjective component is too high. Semi-quantitative method presented by Bolch et al. (2011) and quantitative method presented by Wang et al. (2011) were used according to original methodology described in Sect. 3. For determining whether ice cores are present within the moraine dam using airborne images, we used the method presented by McKillop and Clague (2007a). Unfortunately, it has not been possible to collect the required data for a complete method of hazard assessment. It was also not possible to use the method presented by Mergili and Schneider (2011) because we did not have enough data to calculate the topographic susceptibility index (TSI) and maximum peak ground acceleration (PGA).

3 Approaches to lake and breach hazard assessment

It is difficult to accurately assess whether water will be released catastrophically from a moraine-dammed lake. The

Table 1. Characteristics of studied moraine-dammed lakes in the Cordillera Blanca and input data for hazard assessment.

	Lake (Valley)						Reference
	Quitacocha (Alpamayo)	Checquiacocha (Gatay)	Palcacocha (Cojup)	Llaca (Llaca)	Rajucolta (Rajucolta)	Tararhua (Rurec)	
Lake characteristics							
Altitude [m a.s.l.]	4724	4395	4566	4474	4273	4488	
Volume [mil. m^3]	3.232 (2011)	12.855 (2008)	17.325 (2009)	0.274 (2004)	17.546 (2004)	4.238 (2008)	INRENA/ANA bathymetries
Lake area [$\times 1000\,m^2$]	130.4	351.6	528.4	44.0	512.7	358.0	INRENA/ANA bathymetries
Lake area change	Not significant	Not significant	Significant growth	Significant growth	Not significant	Not significant	Google Earth images
Moraine dam characteristics							
Dam freeboard [m]	>0	0	7	12	14	0	INRENA/ANA bathymetries
Moraine width-to-height ratio	large	large	large	large	large	large	Huggel et al. (2004) methodology
Mean slope of moraine dam [°]	25	18	5	21	23	7	INRENA/ANA reports
Top width of the dam [more than 600 m]	yes	no	no	no	no	yes	Google Earth images
Moraine slopes stabilised by vegetation	no	no	yes	no	yes	no	Google Earth images, field study
Piping/seepage	yes	no	yes	yes	no	no	Field study, INRENA reports
Ice core(s) presence	no	yes	yes	no	no	yes	McKillop and Clague (2007a) methodology
Remedial works	none	none	Open cut, artificial dam	Open cut, artificial dam	Open cut, artificial dam	none	e.g. Reynolds (2003); Carey (2005)
Characteristics related to mother glacier							
Distance between lake and glacier [m]	50 (2005)	370 (2003)	0 (2012)	0 (2012)	0 (2011)	250 (2011)	Google Earth images; field study
Slope between lake and glacier [°]	48	40	–	–	–	34	Calculated from Google Earth
Mother glacier snout steepness [°]	17	28	27	7	24	33	Calculated from Google Earth
Area of the mother glacier [km^2]	0.9	2.1	4.4	1.5	3.0	0.8	Google Earth images
Glacier Shrinkage	Not significant	yes	yes	yes	Not significant	yes	Google Earth images
Characteristics related to lake surroundings							
Possibility of icefall into the lake	yes	yes	yes	yes	yes	yes	Field study; Google Earth images
Possibility of rockfall into the lake	yes	no	yes	yes	no	no	Field study; Google Earth images
Others							
Hydrometeorological situation	High mountain tropical	High mountain tropical	High mountain tropical	High mountain tropical	High mountain tropical	High mountain tropical	Ames and Francou, 1995
Historical GLOFs	None recorded	None recorded	13.12.1941 and 19.3.2003	None recorded	24.6.1883	None recorded	Vilímek et al. (2005b); Zapata (2002)
Previous studies	Matellini (1965)	Matellini (1965)	e.g. Carey (2005); Vilímek et al. (2005a, b)	Electroperu (1973); Reynolds (2003)	Electroperu (1995a); Klimeš (2012)	Electroperu (1995b)	

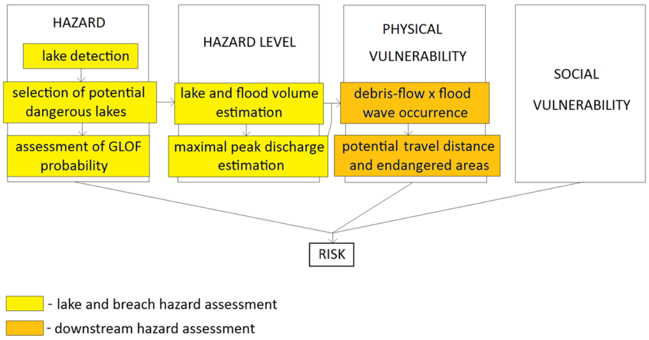

Fig. 2. The procedure for undertaking GLOF hazard, vulnerability, and risk assessment (Sources: Huggel et al., 2004; JTC1, 2004; Hegglin and Huggel, 2008; Richardson, 2010; Shrestha, 2010).

methods of lake and breach hazard assessment usually include two groups of parameters: the first considers the possibility of a triggering event while the second considers the dam stability (Richardson and Reynolds, 2000a; Hegglin and Huggel, 2008; Mergili and Schneider, 2011). It is, of course, possible that a flood may occur even if dam is thought to be stable.

In classic hydrology the flood probability may be derived from its frequency, but this cannot be used in relation to glacial lake outburst floods as they are usually one-off events (Van Steijn, 1996; Hegglin and Huggel, 2008). Clague and Evans (2000), O'Connor et al. (2001), and Huggel et al. (2004) define two stages of GLOF hazard assessment. The first identifies the potentially hazardous lakes and assesses the possibility of water release, the likely flood volume, and probable maximal discharge (i.e. lake and breach hazard assessment). The second examines the downstream hazard and assesses the probability of a debris flow, the reach of the debris flow, and the areas that may be endangered. These areas may then be classified according to their physical vulnerability. It is then possible to undertake a risk assessment for settlements and infrastructure in order to determine physical and social vulnerability (Fig. 2).

There are three approaches to assess the possibility of water release: qualitative; semi-quantitative; and quantitative. The methods are each based upon an evaluation of selected stability parameters (i.e. the stability of the moraine dam, the lake, the area adjacent to the lake, and the glacier feeding the lake). The various stability parameters are summarised in Table 2. It is clear that some parameters are repeated irrespective of the method with the most frequently considered being the distance between the lake and the glacier and the possibility of dynamic slope movements into the lake (e.g. icefalls or rockfalls). These represent the most frequent triggers of GLOFs worldwide (e.g. Awal et al., 2010). The other commonly considered parameters include the geometry of the dam, the freeboard-to-moraine crest height ratio, the moraine width-to-height ratio, and characteristics that describe internal structure of the dam (e.g. piping or the presence of an ice core).

3.1 The qualitative approach

In a qualitative approach, the stability parameters are normally assessed subjectively according to the experience of the individual researcher. The majority of the qualitative methods estimate those stability parameters that are thought to represent an increased hazard. The total number of qualitative parameters considered by those studies outlined here ranges between two and eleven (Table 2). These methods are generally used for preliminary hazard assessments in order to identify potentially hazardous lakes within large previously unstudied areas in which it is not possible to apply another approach. The simplest way to assess the potential hazard is to identify those characteristics indicative of increased hazard. For example, Clague and Evans (2000) showed that the probability of an outburst is high when the dam has a small width-to-height ratio, when outflow occurs mainly through seepage, when there is no armoured overflow channel, when the reservoir surface is normally close to the height of the dam, when there are highly crevassed glaciers clinging to steep slopes directly above the reservoir, and when the slopes above the reservoir are subject to rockfalls. Costa and Schuster (1988) outline four parameters while Grabs and Hanisch (1993) outline eleven parameters that suggest an increased hazard, while Zapata (2002) also introduced list of parameters for hazard assessment.

The simplest method for initially assessing GLOF hazard was presented by O'Connor et al. (2001). This examines only two stability parameters in order to assess the potential for moraine-dam breach, contact with a glacier and the dam freeboard (the vertical distance between the lake level and the lowest point of the moraine crest). These parameters have only two alternatives: "yes" or "no" for contact with a glacier and "high" or "low" for the dam freeboard; the latter is subjective as no critical value delimits "high" from "low". Moreover, this method only considers the most common cause of GLOFs, i.e. icefall into a lake producing surge wave. Nonetheless, four combinations with different aggregate hazards are possible (Table 3).

Huggel et al. (2004) used five stability parameters to obtain the qualitative probability of a GLOF (Table 4). Each parameter was assigned a probability (low, medium, or high), and the overall hazard was considered to reflect the highest probability level attained by any of the five parameters. The parameters were defined subjectively as no critical values were given, with the exception of dam width-to-height ratio. This method has been applied widely by others including researchers working in the vicinity of Mt. Everest (Bolch et al., 2008). In the Cordillera Blanca the method was broadened to include piping and existing remedial measures (Hegglin and Huggel, 2008).

Table 2. The stability characteristics assessed in previous studies.

Stability characteristic	1	2	3	4	5	6	7	8	9	10	11	12	13
Armoured overflow channel (natural or technical)		x		x	x								
Buried ice present in moraine dam		x	x			x		x	x	x	x		
Compound risk present									x				
Crevassed glacier snout above lake		x			x		x						
Dam type			x	x			x						x
Debris-flow occurrence after GLOF*										x			
Distal flank steepness of the dam						x	x	x				x	x
Distance between lake and glacier	x	x					x	x	x	x		x	
Evidence of recent small GLOFs		x											
Flash flood occurrence after GLOF*										x			
Glacier area								x				x	
Glacier advance		x											
Glacier shrinkage										x			
Glacier snout steepness		x					x	x		x		x	
Hydrometeorological situation			x					x					
Lake area							x			x	x		
Lake area change										x			x
Lake depth							x						
Dam freeboard	x	x			x		x						x
Lake freeboard-to-moraine crest height ratio			x	x				x	x				
Lake volume							x		x				
Main rock type forming moraine											x		
Moraine height-to-width ratio											x		
Moraine slopes stabilised by vegetation						x							
Moraine width-to-height ratio			x	x	x		x	x					
Piping/seepage through moraine dam		x		x	x		x		x				x
Possibility of landslide/rockfall into the lake		x			x		x			x			x
Possibility of dynamic slope movements into the lake (ice, rock material)			x			x							
Possibility of snow/ice avalanche into the lake							x		x	x			x
Seismic activity							x						x
Slope between lake and glacier snout												x	
Slopes of lateral moraine/possibility of its fall into the lake		x											
Stagnant ice at the terminus										x			
Supra-/englacial drainage									x				
Top width of dam								x					

1: O'Connor et al. (2001); 2: Grabs and Hanisch (1993); 3: Huggel et al. (2004); 4: Hegglin and Huggel (2008); 5: Clauge and Evans (2000); 6: Costa and Schuster (1988); 7: Zapata (2000); 8: Wang et al. (2008); 9: Reynolds (2003); 10: Bolch et al. (2011); 11: McKillop and Clague (2007a, b); 12: Wang et al. (2011); 13: Mergili and Schneider (2011).
* downstream hazard parameters.

Table 3. The qualitative probability of an outburst defined by O'Connor et al. (2001).

Contact with glacier	Dam freeboard	Outburst potential
No	High	Low
Yes	High	Medium
No	Low	Medium
Yes	Low	High

Wang et al. (2008) used nine stability parameters with defined critical values to investigate two lakes in the Himalaya (Table 5) – these parameters and their critical values were based in part on the work of Lü et al. (1999). The parameters were selected if they were considered to offer a possible mechanism for breaching while the critical values were defined subjectively. It follows that a potential hazard exists whenever a given critical value is exceeded. A number of these values were again used in the qualitative method presented recently by Wang et al. (2011).

3.2 The semi-quantitative approach

In a semi-quantitative approach, the stability parameters are ascribed quantitative scores, but with a large degree of subjectivity. Reynolds (2003) used nine stability parameters (Table 2) with each assigned points according to its influence on the hazard: zero points if there is no impact, two points if there is a low impact, ten points if there is a moderate impact, and fifty points if there is a great impact. The overall hazard is

Table 4. The qualitative probability of a GLOF defined by Huggel et al. (2004).

Stability Characteristics	Alternatives	Probability of GLOF
Dam type	Bedrock Moraine-dammed Ice-dammed	Low Medium to high High
Ratio of freeboard to dam height	High Medium Low	Low Medium High
Ratio of dam width to height	Large (>0.5) Medium (0.2–0.5) Small (0.1–0.2)	Low Medium High
Impact waves by ice- or rockfalls reaching the lake	Unlikely, small volume Sporadic, medium volume Frequent, large volume	Low Medium High
Extreme meteorological events (high temperature or precipitation)	Unlikely Sporadic Frequent	Low Medium High

Table 5. The stability characteristics and their critical values defined by Wang et al. (2008).

Stability characteristics	Critical value	References
Top width of dam	<600 m	Lü et al. (1999)
Distal flank steepness	>20°	Lü et al. (1999)
Ice-core presence	Yes	Richardson and Reynolds (2000b)
Ratio of dam width to height	0.1–0.2	Huggel et al. (2004)
Glacier area	Not stated	Lü et al. (1999)
Slope of glacier snout	>8°	Lü et al. (1999)
Temperature and precipitation	High T, wetness High T, dryness	Lü et al. (1999); Huggel et al. (2004)
Ratio of freeboard to dam height	0	WECS (1987)
Lake–glacier proximity	<500 m	Lü et al. (1999)

then obtained from the total number of points (0: no hazard; 50: minimal; 100: moderate; 125: high; >150: very high). It was considered that an outburst could occur at any time if more than 100 points were recorded. In contrast to Wang et al. (2008), each of the parameters contributes to the overall hazard, irrespective of the fact that no critical values have been defined. However, due to the subjective assignment of points, this method cannot be classified as quantitative.

Bolch et al. (2011) used 11 weighted stability parameters in a study undertaken in Tien Shan. This method required the parameters to be selected, which was done partly on the basis of Huggel et al. (2004) and Bolch et al. (2008). The parameters were then ranked according to their probable influence on the occurrence of a GLOF. In this study the most important was thought to be change in lake area rather than the possibility of an icefall or rockfall (Table 6). The weighting followed a simple linear distribution rule (i.e. the second lowest weight is two times greater than the lowest weight; the third lowest is the sum of the second lowest plus the lowest weight and so on). The weights were multiplied by the value obtained from the assessed stability parameters. The overall hazard is derived from the total sum of these numbers with values of less than 0.1 representing very low hazard, 0.1–0.325 representing low hazard, 0.325–0.574 representing medium hazard, and greater than 0.574 representing high hazard. This method is different to others as it is not specifically a dam breach hazard assessment that aims to determine probability of flood occurrence. Instead, the downstream hazard parameters are also assessed: the occurrences of flash flood and debris flow following outbursts are used as variables in the calculation.

3.3 The quantitative approach

In a quantitative approach, the subjective elements in the hazard assessments are eliminated. McKillop and Clague (2007a, b) assessed hazard through an investigation of 175 moraine-dammed lakes in British Columbia, including 11 in which dams had been breached. In this statistical remote-sensing-based approach, 18 stability parameters

Table 6. The selected stability characteristics and their weights defined by Bolch et al. (2011).

Stability characteristics	Weight	Alternatives
Lake area change	0.1661	Shrinkage (0) Growth <50 % (0.5) Growth <100 % (1) Growth <150 % (1.5) Growth >150 % (2)
Possibility of ice avalanche into lake	0.1510	Yes (1); No (0)
Possibility of rockfall/avalanche into lake	0.1359	Yes (1); No (0)
Ice-cored moraine	0.1208	Yes (1); No (0)
Debris flow	0.1057	Could occur (1); Could not occur (0)
Flash flood	0.0906	Could occur (1); Could not occur (0)
Direct contact with glacier	0.0755	Yes (1); No (0)
Lake area	0.0604	<50 000 m^2 (0.5) 50 000–100 000 m^2 (1) >100 000 m^2 (1.5)
Glacier shrinkage	0.0453	Significant (1); No (0)
Glacier slope <5°at the terminus	0.0302	Yes (1); No (0)
Stagnant ice at the terminus	0.0151	Significant glacier velocity (0); No (1)

were considered. The results compared those lakes in which GLOFs had occurred previously to those in which they had not. Regression analysis showed that only 4 of the 18 stability parameters influenced the possibility of a GLOF: the moraine width-to-height ratio, the presence of an ice core, the lake area, and the main rock type within the moraine. Various alternatives of non-quantitative parameters are replaced by numbers in outburst probability calculation. The weights of these stability parameters were also calculated.

The calculated results (%) and related outburst probabilities are defined as follows: very low probability <6 %; low probability 6–12 %; medium probability 12–18 %; high probability 18–24 %; and very high probability >24 %. This method is essentially based on remote sensing with statistical analysis, although it is not possible to accurately determine the presence an ice core by these means. Therefore, certain morphological assumptions have to be made: a moraine with a rounded surface and minor superimposed ridges was considered to be ice-cored; a disproportionately large end moraine in front of a small glacier was suspected to be ice-cored, while a narrow sharp-crested moraine with an angular cross section was considered to be ice-free (McKillop and Clague, 2007a). It is also not possible to determine the main rock type from remotely sensed data, and so the available geological maps have to be used.

Wang et al. (2011) presented a quantitative method of lake and breach hazard assessment based on an investigation of 78 lakes in the southeastern Tibetan Plateau. In total five stability parameters were assessed (Table 7), although the input data only consider one cause of GLOF – icefall into a lake. The stability parameters were chosen on the basis that they could be measured using the available remotely sensed data, that they acted independently, that the data type was continuous, and that they were consistent with those previously proposed for outburst lakes on the Tibetan Plateau (based on Lü et al., 1999). A fuzzy consistent matrix method was used to determine weighting of these stability parameters. The distance between the lake and glacier was found to be the most important characteristic with a weighting of 0.27 (Table 7). The threshold values were determined for each stability parameter using statistical distribution methods (median, 25th and 75th percentiles) based on the list of values derived from the 78 investigated lakes. The probability of an outburst was calculated as the sum of each individual indicator (see Table 7) multiplied by its respective weighting value. A result of less than 0.5 represents a low potential for outburst, 0.5–0.7 a medium potential, 0.7–0.8 a high potential, and greater than 0.8 a very high potential for outburst flood.

Mergili and Schneider (2011) presented a remote-sensing- and GIS-based method for assessing lake outburst flood hazard in the Pamir region. Eight parameters (Table 2), including lake type, were considered in order to estimate outburst susceptibility (four related to outbursts triggered by external forces and four related to outbursts triggered by internal forces). Critical values were given for all of the parameters (Table 8), and the subjective component is thereby eliminated. The susceptibility to outburst caused by either internal forces or external forces may range from 0 to 4 points (−1, 0, 1 or 2 points for each parameter) while the overall

Table 7. The assessed stability characteristics, their weighting, and threshold values defined by Wang et al. (2011).

	Limit values				Weight (w)
Interval	I	II	III	IV	
Stability characteristics	0.25	0.5	0.75	1	
Area of the mother glacier (km^2)	<0.5	0.5–1	1–2.5	>2.5	0.07
Distance between lake and glacier (m)	>600	300–600	80–300	<80	0.27
Slope between lake and glacier (°)	<12	12–17	17–21	>21	0.22
Mean slope of downstream face of moraine dam (°)	<10	10–14	14–22	>22	0.195
Mother glacier snout steepness (°)	<14	14–19	19–26	>26	0.245

susceptibility to outburst is derived from the matrix of its combination (0–6 points).

4 The study area of the Cordillera Blanca

4.1 Deglaciation and lake development in the Cordillera Blanca

The study area forms part of the high Cordillera Blanca in Peru, the most heavily glacierised tropical range in the world (Ames and Francou, 1995). It is, however, clear that most of the glaciers are retreating. Georges (2004) showed that the total glacial area decreased from 800–850 km^2 in 1930 to 600 km^2 at the end of the 20th century. It is this intense deglaciation (Fig. 3) that has led to an increasing number of potentially hazardous glacial lakes (bedrock, moraine-dammed, ice-dammed) (e.g. Hegglin and Huggel, 2008). The number of significant glacial lakes in the region was 230, of which 119 were moraine-dammed, at the beginning of the 1950s (Concha, 1951). These figures had risen to 267 and 148 by the late 1970s (Morales et al., 1979). It was later found that there were 899 glacial lakes across the region with 424, of which 173 were moraine-dammed, located in the Rio Santa Valley (Portocarrero, 1995). It is now thought that there are more than one thousand glacial lakes in the Cordillera Blanca (A. Cochachin, personal communication, 2012).

It is known that GLOFs have been generated from some of these lakes. The most catastrophic occurred on 13 December 1941 when an *aluvión* occurred as a result of two moraine ruptures at lakes Palcacocha and Jircacocha. It destroyed one-third of the city of Huaraz (Fig. 4) and claimed about 6000 lives (Lliboutry et al., 1977). This event resulted in a number of glacial lake stability studies that investigated the possibility of further outburst floods in the Cordillera Blanca. Such flooding still occurs despite a range of remedial work that has stabilised more than 30 dams (Reynolds, 2003; Carey, 2005). The three most recent events to have caused damage occurred on 19 May 2003 at Lake Palcacocha in the Cojup Valley (Vilímek et al., 2005b), on 11 April 2010 at lake no. 513 in the Hualcán Valley (Carey et al., 2011), and on the 8 February 2012 at lake Artizon Bajo in the Santa Cruz Valley (A. Cochachin, personal communication, 2012).

Fig. 3. The growing Lake Llaca with its retreating glacier and protruding basal moraine.

4.2 The regional specifics of the Cordillera Blanca

It is necessary to consider the regional specifics in order to accurately define the hazard from moraine-dammed lakes (Hegglin and Huggel, 2008). The GLOF triggers are known to vary considerably across the globe. For example, more than one-third of such floods in the North American Cordillera have been caused by intense rainfall/snowmelt (Clague and Evans, 2000; O'Connor et al., 2001), whereas this trigger has never been recognised in the Cordillera Blanca. In this region the most frequent trigger has been

Table 8. The assessed stability characteristics and their critical values defined by Mergili and Schneider (2011).

Stability characteristics (criteria)	Alternatives and critical values	points
Topographic susceptibility index (TSI)	Low (TSI < 10)	0
	Medium (10 ≤ TSI < 40)	1
	High (TSI ≥ 40)	2
Calving into the lake	Is not possible	0
	Is possible	1
Seismic hazard (peak ground acceleration – PGA)	Low (PGA < 500 cm s^{-2})	0
	High (PGA ≥ 500 cm s^{-2})	1
Dam freeboard	High ($F > 25$ m)	−1
	Low ($F \leq 25$ m)	0
Dam material	Embedded lake	0
	Block dam	0
	Debris dam	1
	Rocky swell dam	0
	Glacier or fresh moraine dam	2
Lake drainage	Surface drainage	0
	No surface drainage	1
Lake area development	Stable/shrinking (r_{A1} and $r_{A2} > 0.8$)	0
	Growing (r_{A1} or $r_{A2} \leq 0.8$)	1
Downstream slope of dam	Gentle ($tg\beta < 0.02$)	−1
	Steep ($tg\beta \geq 0.02$)	0

Fig. 4. An aerial photograph of the destroyed city of Huaraz following the *aluvión* from Lake Palcacocha. The area affected is defined by the orange line; the photograph was taken in 1948, seven years after the flood (Source: INRENA/ANA, Project 2524).

icefall into the lake producing displacement waves (45 %) while the second has been landslides or rockfalls into the lake (35 %) (Emmer and Cochachin, 2013). Furthermore, in this area, another important trigger is earthquakes as these may initiate mass movements or cause changes to the internal structure of a moraine dam leading to piping and ultimately dam failure. There have also been instances in which an upstream flood wave has propagated downstream and then caused a GLOF (Vilímek et al., 2005b). This mountain range hosts a number of lakes whose dams have been stabilised by a range of remedial work (Reynolds, 2003; Carey, 2005) (Figs. 5 and 6), and such remediation also has to be considered during the hazard assessment.

From the above and from our previous investigations (Vilímek et al., 2005a, b; Emmer and Cochachin, 2013), it is proposed that the most important groups of parameters that should be included in an assessment of the possibility of water release from moraine-dammed lakes in the Cordillera Blanca are the following:

i. *The possibility of dynamic slope movement into the lake* The first group of dynamic slope movements includes icefalls and avalanches. For a preliminary estimate of whether these slope movements could occur in a lake, it is important to take into account factors such as the distance between the lake and the glacier, the slope between the lake and the glacier, calving, and the slope

Fig. 5. The artificial dam and armoured outflow of Lake Llaca; the dam freeboard is 12 m.

Fig. 6. Lake Palcacocha and its steep lateral moraines, which are predisposed to slope movements, in July 2012. The inset shows the two artificial dams (highlighted in orange) and siphons (black pipes within the lake) constructed during autumn 2011; the dam freeboard is about 9 m.

of the glacier snout. The second group includes landslides, rockfalls, and various types of flows. The most important factors for these movements are thought to be the slope of the internal face of a lateral moraine and the presence of rocks predisposed to rockfalls directly above the lake.

ii. *The distinction between natural dams and dams with remedial works*
In the case of a natural dam, it is necessary to assess the possibility of a dam breach by, for example, assessing the erodibility of the outflow channel(s), the dam geometry, the occurrence of seepage or piping, and the absence or presence of an ice core. In the case of a dam with remedial work, the type of remedial work (tunnel, artificial dam, open cut or canal) should be considered. If a dam with remedial work is considered to be stable (resistant to erosion), there is still the possibility that it will overflow (for this reason it is important to take into account the dam freeboard).

iii. *The dam freeboard (or ratio of dam freeboard)*
A sufficiently large dam freeboard (see Fig. 5) eliminates the possibility of dam overflow when slope movements are transported into the lake while artificial dams often provide additional freeboard that has to be included in a hazard assessment. Furthermore, natural dams without surface outflow are able to partially mitigate displacement waves.

iv. *The possibility of a flood wave from a lake situated upstream*
It may be that a flood wave generated from an upstream lake leads to an outburst flood from a downstream lake even if its dam is considered to be stable and there are no obvious direct triggers (e.g. there is no possibility of a slope movement into the lake). It is, therefore, always important to consider the potential threat posed by upstream lakes.

v. *The possibility of dam rupture following a large earthquake*
The Cordillera Blanca is an active seismic region, and there have been events recorded in which rupture of the moraine dam was initiated by a large earthquake.

5 Results

5.1 The qualitative approach

The results, presented in Table 9, indicate that none of the selected lakes obtained a “full score” of negative stability parameters following the method presented by O’Connor et al. (2001), which would reflect direct contact with glacier and water outflow over the crest of the moraine. It has been found that two lakes obtained two points while the other four obtained three points from a maximum of four points following the method of Costa and Schuster (1988). The other methods also give scores that oscillate close to 50 % with the exception of that obtained for Lake Rajucolta following the method of Clague and Evans (2000). The highest mean score was obtained for Lake Palcacocha (0.602), and it, therefore, appears to offer the greatest potential for flooding and represents the most hazardous lake. It is notable that a flood occurred from this lake in May 2003, and siphons have since been installed to lower the lake level and increase the dam freeboard (Fig. 6).

Table 9. The results of the five qualitative methods investigated in this study (total number of investigated parameters in brackets).

Lake	O'Connor al. (2001) (2)		Costa and Schuster (1988) (4)		Clague and Evans (2000) (6)		Grabs and Hanisch (1993) (11)		Wang et al. (2008) (8)		Arithmetic mean
Quitacocha	0/2	0.00	3/4	0.75	4/6	0.67	5/11	0.45	4/8	0.50	0.474
Checquiacocha	1/2	0.50	3/4	0.75	3/6	0.50	5/11	0.45	4/8	0.50	0.540
Palcacocha	1/2	0.50	3/4	0.75	3/6	0.50	7/11	0.63	5/8	0.63	0.602
Llaca	1/2	0.50	2/4	0.50	3/6	0.50	4/11	0.36	4/8	0.50	0.472
Rajucolta	1/2	0.50	2/4	0.50	1/6	0.17	4/11	0.36	4/8	0.50	0.406
Tararhua	1/2	0.50	3/4	0.75	3/6	0.50	5/11	0.45	5/8	0.63	0.566

Table 10. The results of the semi-quantitative method defined by Bolch et al. (2011).

Lake	Result	Potential for outburst
Quitacocha	0.589	High
Checquiacocha	0.513	Medium
Palcacocha	1.042	High
Llaca	0.612	High
Rajucolta	0.423	Medium
Tararhua	0.513	Medium

Table 11. The results of the quantitative method defined by Wang et al. (2011).

Lake	Result	Potential for outburst
Quitacocha	0.843	Very high
Checquiacocha	0.799	High
Palcacocha	0.854	Very high
Llaca	0.585	Medium
Rajucolta	0.939	Very high
Tararhua	0.751	High

5.2 The semi-quantitative approach

The only semi-quantitative approach used was that of Bolch et al. (2011) as no critical values for an objective lake and breach hazard assessment were defined by Reynolds (2003). It has been found that three of the lakes reflect a medium outburst potential and three a high outburst potential (Table 10). The highest obtained score was that of Lake Palcacocha, mirroring the mean results obtained by the qualitative methods, although its unusually high score may well result from the specific weighting applied as this places considerable emphasis on changes to the lake area. The lowest obtained score was that of Lake Rajucolta again mirroring the mean results obtained by the qualitative methods.

5.3 The quantitative approach

The only quantitative approach used was that of Wang et al. (2011). It has been found that all the lakes reflect medium to very high outburst potential (Table 11). The highest obtained score, contradicting the results obtained by the qualitative and semi-quantitative methods, was that of Lake Rajucolta. This is thought to reflect the fact that this method places considerable emphasis on parameters associated with the mother glacier – Lake Rajucolta is in direct contact with the steep slopes of glacier snout, and, therefore, the outburst potential is classified as very high. Moreover, this method does not consider dam stability, and this is considered to be stable due to the sizeable dam freeboard. Lakes Palcacocha and Quitacocha also obtained scores that indicate a very high outburst potential.

6 Discussion

6.1 The methods of lake and breach hazard assessment

The assessment of the possibility of water release from moraine-dammed lakes is associated with certain problems brought about by variability in some of the stability parameters. This variability may be seasonal (e.g. fluctuations in the lake water level) or irreversible (e.g. slope movements). It is also not possible to quantify some of stability parameters, such as the internal dam structure, without undertaking detailed field study (O'Connor et al., 2001).

The outlined methods can all be applied over large areas, and each has specific advantages so that it is not possible to state which is the most appropriate. In general these methods allow a large number of lakes to be assessed using aerial photography, photogrammetry, and satellite-derived data. The data can be analysed rapidly in geoinformation systems and through modelling. It is clear that different researchers assess hazard using different stability parameters, and these are almost always selected subjectively according to the experience of the researcher and the availability of specific data (the exception to this is the statistical study of McKillop and Clague, 2007a, b). Indeed, the methods are all constrained by data availability, and it is generally considered that this is the most significant limiting factor in hazard assessments.

The majority of the stability parameters can be obtained and assessed reasonably accurately from high-resolution remote sensing images or aerial photographs. There are, however, those that cannot, of which the most commonly required relates to the presence or absence of an ice core within the

Table 12. The methods with regard to whether they take into consideration the regional specifics of the Cordillera Blanca.

Method	A	B	C	D	E
O'Connor et al. (2001)	Partly	No	Partly	No	No
Costa and Schuster (1988)	Yes	No	No	No	No
Clague and Evans (2000)	Yes	Yes	Yes	No	No
Grabs and Hanisch (1993)	Yes	Partly	Partly	No	No
Zapata (2002)	Yes	No	Yes	No	Yes
Huggel et al. (2004)	Yes	No	Yes	No	No
Wang et al. (2008)	Partly	No	Yes	No	No
Hegglin and Huggel (2008)	Yes	Yes	Yes	No	No
Bolch et al. (2011)	Yes	No	No	No	No
Reynolds (2003)	Partly	No	Yes	No	No
Wang et al. (2011)	Partly	No	No	No	No
McKillop and Clague (2007a, b)	No	No	No	No	No
Mergili and Schneider (2011)	Yes	No	Yes	No	Yes

A: possibility of dynamic slope movement into the lake; B: distinction between natural dam and dam with remedial works; C: dam freeboard (or ratio of dam freeboard); D: possibility of flood wave from a lake situated upstream; E: possibility of dam rupture following a large earthquake.

moraine dam. This is an important consideration because it affects dam stability and its internal structure. It cannot be assessed reliably without fieldwork using, for example, ground penetrating radar (Reynolds, 2006) or electric-exploration resistivity (Yamada, 1998). A partial solution may come from the moraine morphology (McKillop and Clague, 2007a), but this is not wholly accurate. In addition, other problematic stability parameters include lake bathymetry, the meteorological regime, the occurrence of piping, and the main rock type forming the moraine. These parameters cannot be determined from remote sensing images, and therefore fieldwork is necessary. It is only with these data that precise hazard assessments for specific lakes can be undertaken. Nonetheless, all of the outlined methods help to recognise potentially hazardous lakes.

The qualitative and semi-quantitative methods include subjective interpretations, and it is thus possible that different researchers may identify different hazards at the same site. The qualitative methods usually have a wide application with no regional focus, whereas the semi-quantitative and quantitative methods frequently focus on specific case studies. These consider the local conditions and causes of GLOFs more carefully than the qualitative methods although some regionally focused methods are replicable in different areas (e.g. McKillop and Clague, 2007a, b). The quantitative approaches are objective and the results are comparable. The characteristics are weighted according to their probable impact on the occurrence of a GLOF or according to their influence on dam stability.

6.2 Methods of hazard assessment and the regional specifics of Cordillera Blanca

In Sect. 4.2 we highlighted five groups of parameters that we consider to be crucial for an accurate regionally focused hazard assessment method for moraine-dammed lakes in the Cordillera Blanca. Table 12 shows the extent to which the summarised methods consider these five criteria. The most suitable methods for use in Cordillera Blanca appear to be those presented by Clague and Evans (2000), Zapata (2002), Hegglin and Huggel (2008), and Mergili and Schneider (2011) as they incorporate three of the five criteria.

The majority of the methods incorporate the most common trigger – dynamic slope movements into the lake – although this group of parameters includes both the possibility of icefall or avalanche into the lake as well as the possibility of rockfall or landslide into the lake. If the outlined method only considered one of these possibilities, the term "partly" was applied. In contrast, most of methods do not incorporate the possibility of downstream flood wave propagation nor the possibility of dam rupture following a large earthquake. These groups of parameters are difficult to quantify and assess, but they are known to have caused GLOFs in the Cordillera Blanca and are, therefore, important to include in a regional hazard assessment. The distinction between natural dams and dams with remedial work has only been incorporated into a small number of methods. It is, therefore, necessary to construct a new method that takes into account all the regional specifics of the Cordillera Blanca so as to provide precise lake and breach hazard assessments relating to the moraine-dammed lakes within this mountain range.

6.3 The results of the lake and breach hazard assessment

The outlined methods show that potentially the most hazardous of the six lakes is Lake Palcacocha, even though this lake has been remediated. This paper, however, has been written so as to summarise contemporary methods of lake and breach hazard assessment for moraine-dammed lakes and discuss their applicability to glacial lakes within the Cordillera Blanca. It has been shown that none of the outlined methods incorporate all of the criteria that we consider crucial for an accurate regional hazard assessment of moraine-dammed lakes in the Cordillera Blanca. We, therefore, recommend that our results are treated tentatively. For example, the method presented by Clague and Evans (2000) was deemed to be one of the most suitable, and this suggests that Lake Quitacocha may be the most hazardous with a score of 0.67.

7 Conclusions

This paper has summarised 13 methods of lake and breach hazard assessment for moraine-dammed lakes: eight are characterised as qualitative, two as semi-quantitative, and three as quantitative. In total seven of the outlined methods have been used to investigate six moraine-dammed lakes within the Cordillera Blanca. These methods show that most hazardous lake is Lake Palcacocha, which is known to have produced two historical GLOFs (1941 and 2003). The results have been obtained despite the fact that the lake has been remediated. The mean of the five qualitative methods gave a result of 0.602; the semi-qualitative method outlined by Bolch et al. (2011) showed a high outburst potential (1.042), whereas the quantitative method outlined by Wang et al. (2011) showed very high outburst potential (0.854). These methods show highly divergent results with regard to Lake Rajucolta. The mean of the five qualitative methods gave a result of 0.406; the semi-qualitative method showed only a medium outburst potential (0.423), whereas the quantitative method showed the greatest outburst potential (0.939).

The moraine-dammed lakes of the Cordillera Blanca are known to be associated with specific characteristics that differ from a number of other regions affected by GLOFs. It is considered that to produce an accurate method of hazard assessment for the moraine-dammed lakes of this region, it is essential to incorporate the following parameters: the possibility of dynamic slope movements into the lake; the possibility of the downstream propagation of a flood wave; the possibility of dam rupture following a large earthquake; the size of the dam freeboard (or ratio of dam freeboard); and a distinction between natural dams and those with remedial work. It is clear that none of summarised methods incorporate all of these parameters with, at most, three of the five included by Clague and Evans (2000), Zapata (2002), Hegglin and Huggel (2008), and Mergili and Schneider (2011).

It is now important to pay particular attention to the problem of glacial lake outburst floods given global climatic change, glacial retreat, the development of new potentially hazardous glacial lakes, and population growth in the Cordillera Blanca. The possibility of water release from a moraine-dammed lake is both difficult to predict and region-specific. The first step in effective hazard mitigation and risk management is to reliably define those lakes that are potentially hazardous. It is, therefore, necessary to construct a new regional lake inventory and method of GLOF hazard assessment for the Cordillera Blanca.

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