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Hazard assessment of GLOFs from moraine-dammed lakes and related debris-flows

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Abstract Glacial lake outburst floods (GLOFs) from moraine-dammed lakes 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 against their catastrophic effects. Three approaches are used in GLOF hazard assessment: (1) qualitative; (2) semi-quantitative; and (3) quantitative. Each has specific advantages and disadvantages. Based on a search of the scientific literature, this paper summarises the various methods of GLOF hazard assessment and outlines their application.

Keywords GLOF, hazard assessment, debris-flow, moraine-dammed lake

Introduction

Glacial lake outburst flood

The term *glacial lake outburst flood* (GLOF) is used to describe the sudden release of water from a glacial lake (e.g. Clauge & Evans, 2000). In Spanish, the broader term *aluvión* is used to describe floods composed of liquid mud with large boulders, irrespective of their cause (Lliboutry et al., 1977; Richardson & Reynolds, 2000a).

The breaching or overflowing of a dam of glacial lake (typically moraine-dammed) causes the sudden release of impounded water (Benn & Evans, 1998; Richardson, 2010). This most frequently results from icefall into the lake (e.g. Costa & Schuster, 1988; Jiang et al., 2004; Awal et al., 2010), although other triggers include landslides or rockfalls (Clauge & Evans, 2000) and the propagation of a flood wave initiated by a breach further upstream (Vilímek et al., 2005b). These scenarios produce significant water displacement and may instigate a surge wave (*seiche* in Hubbard et al., 2005). This may, in turn, cause dam breach or overflow (Richardson & Reynolds, 2000a). Further causes of dam breach include earthquakes (Lliboutry et al., 1977), the melting of buried ice (Richardson & Reynolds, 2000b), intense rainfall or snowmelt (Yamada, 1998), and blockages in underground outflow channels (O'Connor et al., 2001; Janský et al., 2006).

This phenomenon has been studied in high mountainous areas across the globe, including the Himalaya (Kattelmann & Watanabe, 1997; Yamada, 1998; Bajracharya et al., 2007), Karakoram (Hewitt, 1982), Hindu-Kush (Iturrizaga, 2005; Ives et al., 2010), Tian-Shan (Janský et al., 2008; Narama et al., 2010, Bolch et al, 2011), Caucasus Mts. (Petrakov et al., 2007), Peruvian Andes (Fig. 1)(Lliboutry et al., 1977; Reynolds, 2003; Vilímek et al., 2005a), Cascade Range (O'Connor et al., 2001), and British Columbia (Clauge & 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).

Fig. 1 Current state of the Palcacocha Lake (outburst in 1941)

Relation to debris-flows

The maximal discharge of a GLOFs may exceed tens of thousands of m^3/s (Costa & Schuster, 1988) and are characterised by high erosion and transport potential (Cenderelli & Wohl, 2001; Breien et al., 2008). As a consequence, GLOFs are able to transform easily into debris-flows (O'Connor et al., 2001) with densities of about 1.5 t/m^3 (Yamada, 1998). The volume of the transported material may exceed millions of cubic meters (Evans et al., 2002; Hubbard et al., 2005). Whether a GLOF transforms into a debris-flow depends on many factors, most particularly on the erosional potential of the flood wave and the amount of erodible material deposited within the affected valley. The distinction between flood and debris-flow is, in fact, somewhat arbitrary.

It is clear that glacial lake outburst floods and related debris-flows are significant geomorphic processes that represent a considerable threat to the inhabitants of high mountainous areas. Therefore, allied with intense deglaciation in many areas, these processes require the appropriate attention. It is necessary to study these phenomena thoroughly so as to mitigate against their catastrophic effects or, ideally, to be able to prevent them completely. The most important step in GLOF hazard mitigation is to recognise and reliably assess the potential hazard.

Methods

Contemporary approaches to hazard assessment of GLOFs from moraine-dammed lakes are summarised and compared in this paper. In classic hydrology, the probability of a flood may be derived from its frequency. However, GLOFs require a distinct procedure, as they are usually one-off events (Van Steijn, 1996; Hegglin & Huggel, 2008).

In a GLOF hazard assessment, it is necessary to include two main groups of parameters. The first considers the possibility of a triggering event whilst the second considers the stability of the dam (Richardson & Reynolds, 2000a; Hegglin & Huggel, 2008). If we want to study the probability of a GLOF-induced debris-flow, it is first necessary study the probability of a GLOF (i.e. the hazard). There are three approaches to assessing this probability: (1) qualitative; (2) semi-quantitative; and (3) quantitative.

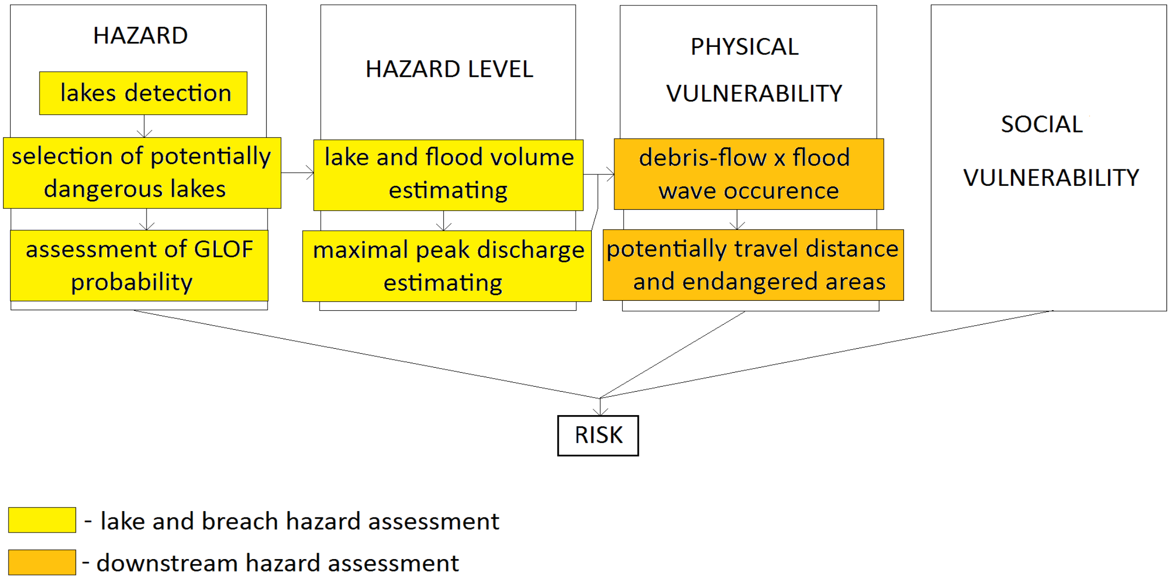


Figure 2 The procedure for undertaking GLOF hazard, vulnerability, and risk assessment (sources: Huggel et al. (2004); JTC1 (2004); Hegglin & Huggel (2008); Richardson (2010); Shrestha (2010))

Results

The methods within each approach (qualitative, semi-quantitative, and quantitative) are based on an evaluation of selected stability characteristics (i.e. the stability of the dam characteristics, the lake characteristics, the area adjacent to the lake charactecristics, and the glacier feeding the lake characteristics). These characteristics may be given greater or lesser emphasis depending on the specific method. The stability characteristics considered in the GLOF hazard assessment literature have been summarised and are presented in Tab. 8. Clauge & Evans (2000), Huggel et al. (2004) and others define two phases of GLOF hazard assessment. The first phase aims to identify potentially dangerous lakes and assesses the probability of a flood occurrence, its volume, and probable maximal discharge (i.e. lake and breach hazard assessment). The second phase aims to examine the downstream hazard and assesses the probability of a debris-flow occurrence, the distance it may travel, and identifies the areas that may be endangered. These areas may then be classified on the basis of physical vulnerability. Following the hazard assessment, it is then possible to undertake a risk assessment for settlements and infrastructure in order to determine physical and social vulnerability (Fig. 2).

Qualitative approach

In a qualitative approach, the stability characteristics are selected subjectively on the basis of the individual researcher's previous experience. This methods are useful for preliminary hazard assessment so as to identify potentially hazardous lakes over large previously unstudied areas where it is not possible to apply another approach.

The simplest way to assess the potential hazard is to identify characteristics indicative of increased hazard. For example, Clauge & 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. In contrast, Costa & Schuster (1988) outline four characteristics that suggest an increased hazard, Grabs & Hanisch (1993) outline thirteen characteristics, and Zapata (2002) outlines fourteen characteristics. The selected stability characteristics for each method are listed in Tab. 8.

A very simple method that can be used to initially assess the GLOF hazard was presented by O'Connor et al. (2001). This method assesses the potential for moraine-dam breach by examining only two stability characteristics, contact with a glacier and the dam freeboard (vertical elevation between the lake level and the lowest point of the moraine crest). These characteristics only have two alternatives, “yes” or “no” for contact with a glacier and “high” or “low” for the dam freeboard. Clearly 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 (Tab. 1).

Table 1 The qualitative probability of an outburst defined by O'Connor et al. (2001)

CONTACT WITH GLACIER	DAM FREEBOARD	OUTBURST POTENTIAL
No	High	Low
Yes	Low	Medium
No	High	Medium
Yes	Low	High

Huggel et al. (2004) assessed five stability characteristics in order to derive the qualitative probability of a GLOF (Tab. 2). Each of these characteristics was associated with either a low, medium, or high probability. The overall hazard was derived from the highest probability level attained by any of the given characteristics. With the exception of dam width-to-height ratio, no critical values were given and the characteristics are thus defined subjectively. This method has been widely applied by other authors, such as those working in Tien Shan and Mt.Everest region (Bolch et al., 2008; Janský et al., 2010). Hegglin & Huggel (2008) also applied the principles of this method in the Cordillera Blanca. However, in that study the method was broadened to also include piping and the existing technical measures on the dam.

Table 2 The qualitative probability of a GLOF defined by Huggel et al. (2004)

STABILITY CHARACTICS	ALTERNATIVES	PROBABILITY OF A GLOF
Dam type	Bedrock	Low
	Moraine-dammed	Medium to high
	Ice-dammed	High
Ratio of freeboard to dam height	High	Low
	Medium	Medium
	Low	High
Ratio of dam width to height	Large (> 0.5)	Low
	Medium (0.2-0.5)	Medium
	Small (0.1-0.2)	High
Impact waves by ice or rock falls reaching the lake	Unlikely, small volume	Low
	Sporadic, medium volume	Medium
	Frequent, large volume	High
Extreme meteorological events (high temperature or precipitation)	Unlikely	Low
	Sporadic	Medium
	Frequent	High

Wang et al. (2008) investigated two lakes in the Himalayas using nine stability characteristics with defined critical values (Tab. 3). These stability characteristics were selected if they were considered to provide a possible mechanism for breaching on the basis of previous research into breached moraine-dammed lakes both in the Himalayas and elsewhere. The critical values were determined subjectively and exceeding any given critical value implies a potential hazard.

Table 3 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 & 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

Semi-quantitative approach

In a semi-quantitative approach, the subjective choice of stability characteristics benefits from calculations of the specific critical values and/or numeric hazard computation. Reynolds (2003) assessed nine stability characteristics (Tab. 8). For each characteristic, points were assigned according to their 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 derived from the total sum of these points (Tab. 4). If there were more than one hundred points, it was considered that an outburst could occur at any time. In contrast to Wang et al. (2008), each characteristic considered using this method is included in the overall hazard, despite the fact that no critical values were determined.

Table 4 The total sum of points and the overall hazard defined by Reynolds (2003)

SUM	0	50	100	125	150 <
HAZARD	Zero	Minimal	Moderate	High	Very high

Bolch et al. (2011) assessed eleven weighted stability characteristics in a study undertaken in Tien Shan. This method required the characteristics to be selected, and this was done partly on the basis of Huggel et al. (2004) and Bolch et al. (2008). The characteristics were then ranked according to their probable influence on the occurrence of a GLOF. The most important characteristic was thought to be change in lake area rather than the posibility of an icefall or rockfall (Tab. 5). The weighting was assigned according to a simple linear distribution rule, i.e. the 2nd lowest weight is two times greater than the lowest weight, the 3rd lowest is the sum of the 2nd lowest plus the lowest weight and so on. The weights were multiplied by the value obtained from the assessed stability characteristics. The overall hazard is derived from the total sum of these numbers. Values of less than 0.1 represent very low hazard, 0.1-0.325 represent low hazard, 0.325-0.574 represent medium hazard, and greater than 0.574 represent high hazard. This method is specific and different from others as it is not a dam breach hazard assessment that aims to determine probability of flood occurrence. Instead, downstream hazard parameters are also assessed: the occurrence of floods and debris-flows following outbursts are used as variables in calculation.

Table 5 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)

Quantitative approach

In a quantitative approach, the subjective elements in the aforementioned approaches are eliminated. McKillop & Clauge (2007a,b) assessed hazard through an investigation on 175 lakes in British Columbia, including eleven in which dams had been breached. These had a total lake area of more than 10 000 m². Eighteen stability characteristics were considered. The results compared those lakes in which GLOFs had previously occurred to those in which they had not. Regression analysis showed that only four of the eighteen stability characteristics influence the possibility of a GLOF. In addition, the weights of these stability characteristics were calculated. The equation for estimating outburst probability was expressed as:

$$P(Y=1)=\{1+\exp-[\alpha+\beta_1(\text{moraine width to height ratio}) +\Sigma\beta_j(\text{ice core presence})+\beta_2(\text{lake area}) +\Sigma\beta_k(\text{main rock type forming moraine})]\}^{-1} \quad [1]$$

In this equation α is the intercept, β_1, β_2, β_j, β_k are calculated regression coefficients. The measured values can be entered directly into the equation (e.g. moraine width-to-height ratio and lake area). Different coefficients for the various moraine-forming rock types were also determined (granitic x volcanic x sedimentary x metamorphic). If the moraine dam is ice-cored, 1 is entered into equation; if it is not, 0 is entered. The calculated results (%) and related outburst probabilities are shown in Tab. 6.

Table 6 The calculation results and outburst probabilities defined by McKillop & Clauge (2007a)

RESULT	< 6 %	6-12 %	12-18 %	18-24 %	> 24 %
OUTBURST PROBABILITY	Very low	Low	Medium	High	Very high

Although this method was presented as being based on remote-sensing with statistical analysis, it is not possible to determine the presence or absence of an ice core by these means. Therefore, certain morphological assumptions had to be made. First, a moraine with a rounded surface and minor superimposed ridges was considered to be ice-cored. Second, a disproportionately large end moraine in front of a small glacier was suspected to be ice-cored. Third, a narrow sharp-crested moraine with an angular cross section was interpreted to be ice-free. In addition, the main rock type cannot be determined from remotely sensed data. In British Columbia, available geological maps were used.

Wang et al. (2011) presented a quantitative method of GLOF hazard assessment based on an investigation of 78 lakes in the southeastern Tibetan Plateau. Five stability characteristics were assessed (Tab. 7). With regard to the input data, this method only considers one cause of GLOF, icefall into lake. The stability characteristics were chosen on the basis that they could be measured using available remotely sensed data, they were consistent with those previously proposed for outburst lakes on the Tibetan Plateau (based on Lü et al., 1999), they acted independently, and the data type were continuous rather than nominal.

The next step was to determine weighting of these stability characteristics. For this, a fuzzy consistent matrix method was used. The distance between the lake and glacier was determined as the most important characteristic with a weighting of 0.27 (Tab. 7) as this reflects the possibility of icefall into lake. The threshold values were determined for each stability characteristic using statistical distribution methods (median, 25th and 75th percentiles) based on the list of values derived from the seventy eight investigated lakes. To assess the outburst probability, the following equation was used:

$$P=\sum_{i=1}^{5} w_i \cdot V_i \qquad [2]$$

where w_i is the weight of stability characteristics, V_i is derived from Tab. 7. A result of less than 0.5 represents a low potential for outburst, 0.5-0.7 represents a medium potential, 0.7-0.8 represents a high potential, and greater than 0.8 represents a very high potential for outburst flood.

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 CHARACTERISTIC	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 moraine dam (°)	< 10	10-14	14-22	> 22	0.195
Mother glacier snout steepness(°)	< 14	14-19	19-26	> 26	0.245

Discussion

Hazard assessment of GLOFs from moraine-dammed lakes and related debris-flows are associated with certain problems brought about by variability in some of the stability characteristics. This variability may be seasonal (e.g. fluctuations of water level in the lake depending on the amount of rainfall or snowmelt) or irreversible (e.g. slope movements). It is also not possible to quantify some of stability characteristics, such as the internal dam structure (O'Connor et al., 2001). In addition, regional differences make it difficult to construct a universal hazard assessment method, a problem that is exacerbated as new regionally-specific methods continue to be developed.

Input data

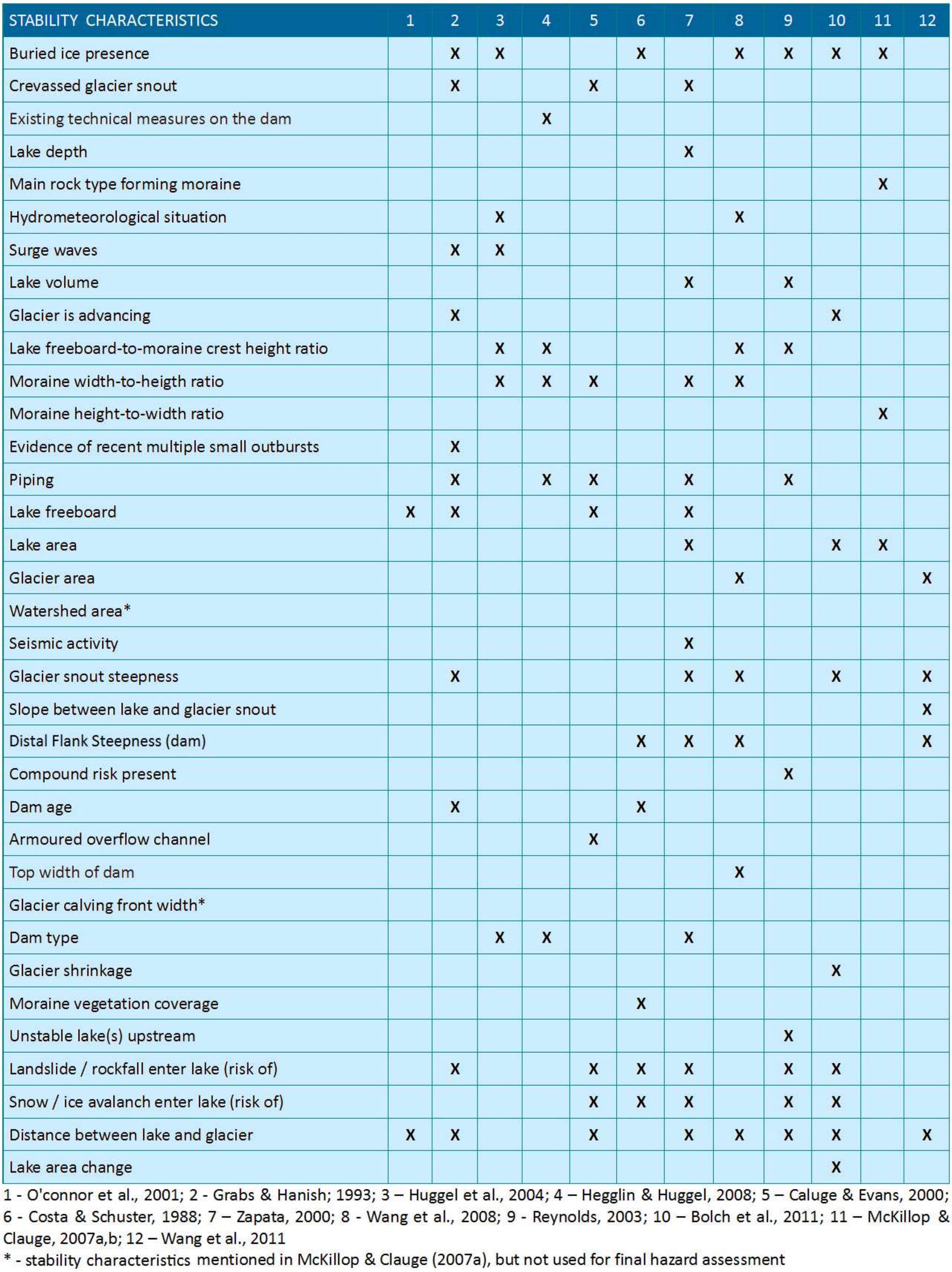
Different authors assess hazard with the use of different input data, i.e. the stability characteristics. In all the aforementioned methods, these characteristics are selected subjectively based on the authors previous experience and data availability (the exception to this are the statistical study of McKillop & Clauge (2007a,b)). All these methods are constructed subject to data availability and we find that this is the most limiting factor in hazard assessments.

Most of stability characteristics can be, more or less, accurately derived and assessed from high resolution remote-sensing or aerial photographs. Clearly, some cannot; of these, one most frequently required for hazard assessment is information relating to the presence or absence of an ice core. This is important as it affects dam stability and determines the significance of ice melt. However, it cannot be assessed reliably without fieldwork (e.g. using ground penetrating radar (Reynolds, 2006) or electric-exploration resistivity method (Yamada, 1998)). A partial solution may come from the moraine morphology (McKillop & Clauge, 2007a) but this is not wholly accurate. In addition, other problematic stability characteristics include lake bathymetry (depth and volume), the meteorological regime, the occurrence of piping, and the main rock type that forms the moraine.

Causes of GLOFs and regional specifics

The causes of GLOFs from moraine-dammed lakes vary considerably across the globe. Generally, in all regions, main cause is icefall into a lake producing a displacement wave (e.g. Ding & Liu, 1992; Clauge & Evans, 2000). It is thought that this causes about half of all GLOFs. In calculating hazard, other causes are not usually taken into consideration. These causes reflect considerable regional differences. For example, more than one third of GLOFs in the North-American Cordillera are caused by intense rainfall or snowmelt (O'Connor et al., 2001; Clauge & Evans, 2000) whereas this has not been recorded in the Cordillera Blanca of Peru (Zapata, 2002). The most recent GLOF occured in Cordillera Blanca under Hualcán Mt. during April 11th 2010 and was

Table 8 Stability aspects and methods of hazard assessment



STABILITY CHARACTERISTICS	1	2	3	4	5	6	7	8	9	10	11	12
Buried ice presence		X	X			X		X	X	X	X	
Crevassed glacier snout		X			X		X					
Existing technical measures on the dam				X								
Lake depth							X					
Main rock type forming moraine											X	
Hydrometeorological situation			X					X				
Surge waves		X	X									
Lake volume							X		X			
Glacier is advancing		X								X		
Lake freeboard-to-moraine crest height ratio			X	X				X	X			
Moraine width-to-heigth ratio			X	X	X		X	X				
Moraine height-to-width ratio											X	
Evidence of recent multiple small outbursts		X										
Piping		X		X	X		X		X			
Lake freeboard	X	X			X		X					
Lake area							X			X	X	
Glacier area								X				X
Watershed area*												
Seismic activity							X					
Glacier snout steepness		X					X	X		X		X
Slope between lake and glacier snout												X
Distal Flank Steepness (dam)						X	X	X				X
Compound risk present									X			
Dam age		X				X						
Armoured overflow channel					X							
Top width of dam								X				
Glacier calving front width*												
Dam type			X	X			X					
Glacier shrinkage										X		
Moraine vegetation coverage						X						
Unstable lake(s) upstream									X			
Landslide / rockfall enter lake (risk of)		X			X	X	X		X	X		
Snow / ice avalanch enter lake (risk of)					X	X	X		X	X		
Distance between lake and glacier	X	X			X		X	X	X	X		X
Lake area change										X		

1 - O'connor et al., 2001; 2 - Grabs & Hanish; 1993; 3 – Huggel et al., 2004; 4 – Hegglin & Huggel, 2008; 5 – Caluge & Evans, 2000; 6 - Costa & Schuster, 1988; 7 – Zapata, 2000; 8 - Wang et al., 2008; 9 - Reynolds, 2003; 10 – Bolch et al., 2011; 11 – McKillop & Clauge, 2007a,b; 12 – Wang et al., 2011

* - stability characteristics mentioned in McKillop & Clauge (2007a), but not used for final hazard assessment

triggered by icefall into lake. Erosion and accumulation processes from this GLOF are visible on the Figure 3. As Hegglin & Huggel (2008) pointed out, it is necessary to consider regional specifics in order to be able to accurately define the hazard of GLOFs from moraine-dammed lakes.

Qualitative methods usually have wide application with no regional focus whereas semi-quantitative and quantitative methods frequently focus on specific study areas and closely consider the local conditions and local causes of GLOFs. Some of procedures for creating regionally-focused methods are replicable in different regions, such as the quantitative method published by McKillop & Clauge (2007a).

Fig. 3 Erosion and accumulation processes from GLOF occured in Cordillera Blanca under Hualcán Mt. during April 11th 2010

Conclusions

The aforementioned methods are all applicable over large areas. Each has specific advantages and no single method is considered to be the most appropriate. In general terms, these methods allow a large number of lakes to be assessed using aerial photography, photogrammetry, and remotely sensed data. These data can be analysed in geoinformation systems and through modelling. The methods are relatively rapid and inexpensive.

The qualitative and semi-quantitative approaches include subjective elements. Thus, it is possible that different observers could define different hazards to the same lake. The quantitative approaches are objective and provide more accurate information about the potential hazard, which is determined from a statistical calculation. The characteristics are weighted according to their probable impact on the occurrence of a GLOF or according to their influence of dam stability. Nonetheless, they still depend on accurate input data. In remote high mountainous areas, reliable data acquisition may represent a problem.

All the discussed methods help to initially recognise potentially dangerous lakes. Grabs & Hanisch (1993) emphasised that it is still necessary to undertake fieldwork in order to obtain detailed information about lake dam stability and the possible causes of GLOFs, despite contemporary developments in remote sensing. With these data, precise hazard assessments for specific lakes can be undertaken.

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