

# THE CAUSES AND MECHANISMS OF MORaine-DAMMED LAKE FAILURES IN THE CORDILLERA BLANCA, NORTH AMERICAN CORDILLERA, AND HIMALAYAS

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## ABSTRACT

Glacial lake outburst floods (GLOFs) from moraine-dammed lake failures represent a significant threat to inhabitants of high mountain areas across the globe. The first part of this paper summarises the causes and mechanisms of moraine-dammed lake failures through a review of the scientific literature and unpublished reports. There are eight main causes, of which five are characterised as dynamic and three as long-term, and these are associated with around twenty failure mechanisms. The dynamic causes are slope movements into the lake, earthquakes, flood waves from a lake situated upstream, blocking of underground outflow channels, and intensive rainfall or snowmelt. The long-term causes are the melting of buried ice, the impact of hydrostatic pressure, and the effect of time. These causes (triggers) and the consequent mechanisms of dam failure are described in detail. The second part compares the historical moraine-dammed lake failures within three regions between 1900 and 2009: the Cordillera Blanca of Peru, the North American Cordillera, and the Himalayas. It has been found that dynamic causes are around four times more common than long-term causes although significant regional differences have been observed. The most frequent causes in these regions were found to be slope movements in which the displaced material was dominated by solid-state water (ice falls, ice avalanches, and snow avalanches). The other causes tended to show distinct regional patterns while the temporal distribution of events also differs according to region. In the North American Cordillera and Himalayas moraine dam failures occur exclusively during the summer season while in the Cordillera Blanca they are more evenly distributed with the exception of the dry season. This reflects the general climatic setting of each of the study regions.

**Keywords:** moraine-dammed lakes, natural dam failures, GLOFs, natural hazards, high mountain areas

## 1. Introduction

In this study moraine-dammed lakes are defined as natural freshwater reservoirs dammed by material accumulated from a glacier (the moraine). This type of lake is not considered to be particularly stable because the morainic material forming the dam is usually unconsolidated and, therefore, even a relatively weak trigger can cause the dam to fail, leading to a glacial lake outburst flood (GLOF) (e.g. Costa & Schuster 1988; Richardson & Reynolds 2000a; Shrestha 2010). This form of flood describes the sudden water release from any form of glacial lake (e.g. bedrock-dammed, moraine-dammed, or ice-dammed) irrespective of its cause (Benn & Evans 1998). These floods are characterised by peak discharges that are many times higher than those of a hydrometeorological flood (Clauge & Evans 2000). They, therefore, have the potential to be highly catastrophic. GLOFs may occur as a result of dam failure (moraine-dammed or ice-dammed) or dam overflow (all types of glacial lake).

The study of moraine-dammed lake failure is complex and requires interdisciplinary cooperation. It is appreciated that two main groups of parameters are decisive in contributing to a moraine dam failure, the first is that of dam stability and the second is the possibility of a triggering event (Richardson & Reynolds 2000a; Hegglin & Huggel 2008). These are difficult to assess and quantify which leads to problems in estimating the probability

of a moraine dam failure (hazard assessment) (Emmer & Vilímek 2013). It is possible for a moraine dam failure to be total or partial and, therefore, a given lake can be subjected to repeated GLOFs (O'Connor et al. 2001; Bajracharya et al. 2007a). GLOFs represent an increasingly significant threat in high-mountain areas because the number of potentially dangerous glacial lakes is increasing as a result of global climate change and concurrent glacier retreat (e.g. Evans & Clauge 1994; Bolch et al. 2008; Ives et al. 2010).

GLOFs from moraine-dammed lake failures have been studied in high-mountain regions all over the world including the Himalaya (Vuichard & Zimmerman 1987; Kattelmann & Watanabe 1997; Bajracharya et al. 2007a,b), Hindu-Kush (Iturrizaga 2005; Ives et al. 2010), Karakoram (Hewitt 1982), Tian-Shan (Janský et al. 2009; Narama et al. 2010; Bolch et al. 2011), Caucasus Mts. (Petrakov et al. 2007), Cascade Range (O'Connor et al. 2001), British Columbia (Clauge & Evans 2000; Kershaw et al. 2005), Peruvian Andes (Zapata 1984; Vilímek et al. 2005a; Carey et al. 2011; Klimeš 2012), Patagonia (Harrison et al. 2006; Dussailant et al. 2009) as well as in the European Alps (Haeberli et al. 2001; Huggel et al. 2004) and Scandinavia (Breien et al. 2008). The objectives of this paper are to provide an overview of moraine-dammed lake failures, to investigate their causes and mechanisms, and to compare the temporal aspect of these events within three

regions: the Cordillera Blanca of Peru, the North American Cordillera, and Himalaya. These areas were chosen because they have a long history of moraine-dammed lake research and there is, therefore, a greater chance of acquiring information about GLOFs. The flooding that occurs as a result of moraine-dammed lake failures poses a significant threat in high mountain regions and by comparing events it is possible to recognise the regional specifics that are necessary in order to build an optimal regionally focused hazard assessment.

**2. Materials and methods**

The causes (triggers) and mechanisms of moraine-dammed lake failures are summarised following an extensive search of the published scientific literature and unpublished reports from the archive of the Autoridad Nacional de Agua in Huaraz, Peru. These causes and consequent mechanisms of dam failure are described in detail with examples given for each. The similarities and disparities that exist between the particular causes have been investigated as well as the temporal characteristics of events in the Cordillera Blanca of Peru, the North American Cordillera, and Himalaya. The GLOF database (GLOFs database 2012) has been used as the basis for this comparative analysis: the details of around ninety-five moraine dam failures within the three study areas have been compiled for the period 1900 to 2009. The causes of the GLOFs are known in sixty of these cases (twenty in Cordillera Blanca of Peru, eleven in the North American Cordillera, and twenty-nine in Himalaya) but unknown in the other instances. The precise dates of the GLOFs are known in sixty-six of the cases and can be attributed to a year in seventy-five instances. The temporal characteristics of the GLOFs are considered both in terms of their monthly and annual distributions.

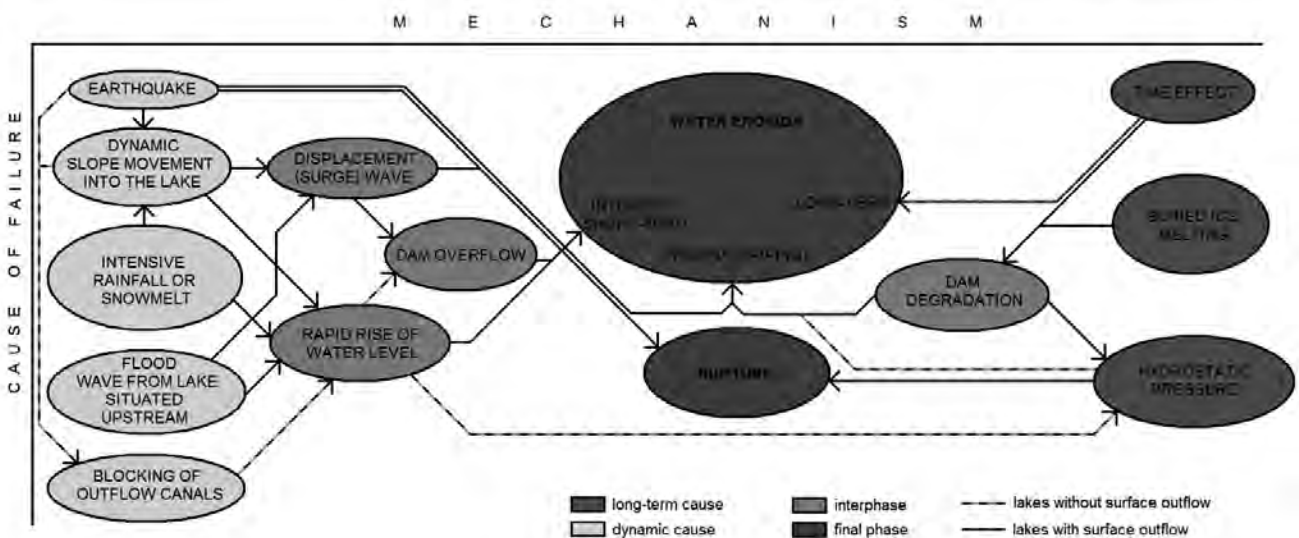
**3. The causes and mechanisms of moraine-dammed lake failures**

There is a close relationship between various types of natural hazards and moraine-dammed lake failures that result in GLOFs. The former, the various natural hazards, often represent the cause of the latter, the lake failures. These relationships are summarised in Figure 1. Yamada (1998) divided the process of moraine dam failure into two groups: the first consisted of dam failure caused by a dynamic initiating event while the second consisted of spontaneous “dam self-destruction”. The latter group are caused by long-term degradation of the dam without a dynamic initiating event. This grouping is followed here and the causes of moraine dam failure are classified as either dynamic causes or long-term.

**3.1 The dynamic causes of moraine-dammed lake failures**

The dynamic causes are slope movements into the lake, earthquakes, a flood wave from a lake situated upstream, blocking of underground outflow channels, and intensive rainfall or snowmelt. In this group the time interval between the trigger and the moraine dam failure ranges from minutes in the case of, for example, a slope movement into the lake to hours or days in the case of, for example, intensive rainfall or snowmelt. These dynamic causes were termed “quasicoincidental” by O’Connor et al. (2001) as it is not possible to accurately predict the time or place in which they will occur.

The slope movement into the lake includes various types of mass-movement such as icefalls, avalanches, rockfalls, landslides, debris flows, and mudflows. The mass of material entering the lake causes water displacement in the form of surge (displacement) waves (Richardson & Reynolds 2000a) and these can reach heights of tens of metres (Plafker & Eyzaguirre 1979 in Costa & Schuster



**Fig. 1** The causes and mechanisms that underpin the process of moraine dam failure.

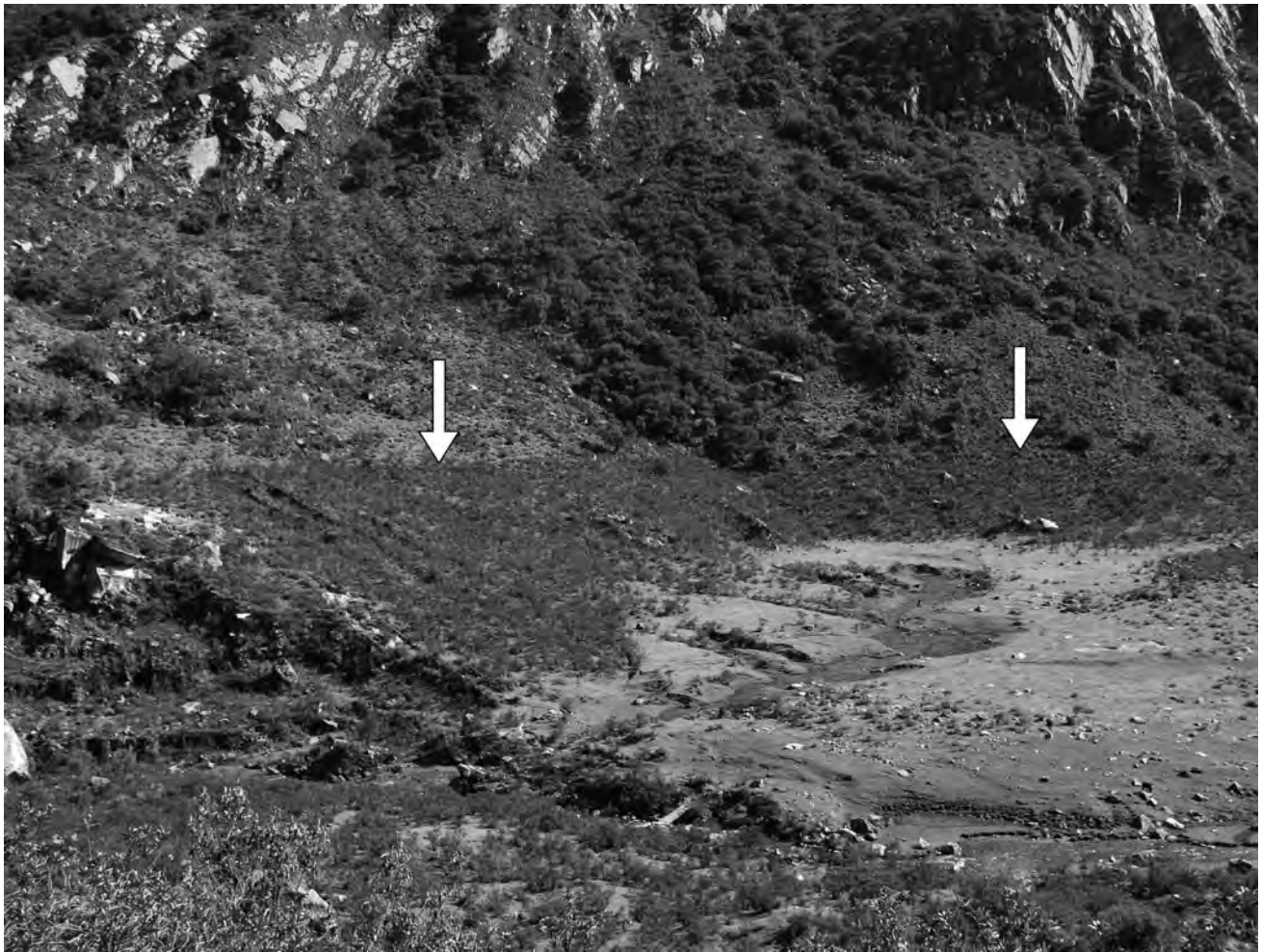
1988). The waves have a considerable impact on the stability of the moraine-dam (e.g. Kattelmann & Watanabe 1997; Clauge & Evans 2000). The slope movement into the lake and its related displacement wave may lead to two different mechanisms of dam failure. The first is that of immediate dam rupture following the impact of the displacement wave and this represents the most catastrophic scenario while the second is that of dam failure due to an increase in outflow channel discharge. The second mechanism is essentially caused by the increased water level within the lake which increases the outflow channel discharge and causes increased incision which then, in turn, increases the discharge and increases the incision. This “positive feedback” (Yamada 1998) continues until the outflow channel is either able to resist the incision due to structural changes or until the lake empties (Clauge & Evans 2000). However, if the displacement wave has the necessary energy and moraine dam is at the same time sufficiently resistant, flooding may result from dam overflow (Kershaw et al. 2005). This may happen without significant damage to the moraine dam and an example occurred on 22nd April 2002 as a result of rockfall into lake Safuna Alta in the Cordillera Blanca (Hubbard et al. 2005). It is possible for dam overflow and outflow channel incision caused by sudden rise of the water level to occur during the same flood event. Kershaw et al. (2005) presented stratigraphical and sedimentological evidence from the Queen Bess lake GLOF on 12th August 1997 that indicated both scenarios. The first phase of flooding was represented by dam overflow during which the bulk of the flood volume escaped (Clauge & Evans 2000) while the second phase was represented by dam incision and final failure. The time interval between these phases was in order of minutes (Evans et al. 2002).

It is possible for an earthquake to directly initiate a moraine-dammed lake failure as the shock can cause sufficient damage to a dam for it to fail (Clauge & Evans 2000) while there is also the chance that the seismic activity may initiate slope movements. In some cases it is not known whether dam failure was caused directly by an earthquake or if it was caused by slope movements initiated by an earthquake and this is particularly difficult to distinguish in the case of historical events (Strasser et al. 2008). There is also the chance that an earthquake could change the internal structure of the moraine dam causing internal erosion in the form of piping which may then lead to the emptying of the lake (Lliboutry et al. 1977). In contrast, changes in the internal structure of the dam may serve to reduce infiltration through the moraine by blocking underground outflow channels. This may be dangerous in instances where the lake does not have a surface outflow as there is then a continuous rise in lake water level. It was seen at lake Parón (Cordillera Blanca) when an earthquake in 1966 inhibited flow along underground channels and the water level rose steadily until next strong earthquake in 1970 when discharge turned into the values before 1966 event (Lliboutry et al. 1977).

The flood wave from an upstream lake can cause dam failure on a lake situated downstream. The flood wave can often transform easily into different types of flows because of its high erosion and transport potential (Cenderelli & Wohl 2001; Breien et al. 2008). It produces a displacement wave or a significant rise in the water level when entering the downstream lake and this has the same consequences as a slope movement into the lake. A dam failure may occur as a result of the direct impact of the displacement wave or following incision of the outflow channels. The overall flood volume often considerable in these cases as there are inputs from two lakes. This was seen in the Cordillera Blanca following the Palcacocha outburst flood which destroyed the downstream lake Jircacocha on 13th December 1941 (Vilímek et al. 2005b) (Figure 2). The catastrophic debris-flow incorporated water from both lakes and destroyed one-third of the city of Huaraz claiming about 6000 lives (Lliboutry et al. 1977). However, in some cases, the downstream lake may absorb the flood wave if it has a sufficiently large accommodation space. It is known that lake Parón in the Cordillera Blanca has been able to absorb outburst floods from two lakes, the first from lake Chacrucocha prior to 1950 and second from lake Artesoncocha in 1951 (Lliboutry et al. 1977; Carey et al. 2012).

The blocking of underground outflow channels can be caused by four mechanisms: clogging by sediments brought into the lake by its tributaries; clogging by material brought into the lake during mass-movements; freezing of outflow channels (O'Connor et al. 2001); and blocking of outflow channels caused by the changing internal structure of dam due to an earthquake (Lliboutry et al. 1977). The water level of the lake starts to rise if the channels are blocked and this leads to the same mechanism of dam failure as occurs during intense rainfall or snowmelt – dam rupture caused when the lithostatic pressure exceeds that of hydrostatic pressure (Richardson & Reynolds 2000a). There will also be increased erosion in instances of dam overflow. However, unlike the rise in water level caused by intense rainfall or snowmelt, the blocking of underground outflow channels usually causes the water level to increase until the lake basin is full. This occurs unless the hydrostatic pressure exceeds the lithostatic pressure as blocked channels do not usually unblock spontaneously. The moraine dam failure at lake Zhangzhanbo in Tibet on 11th July 1981 was caused by blocking of underground outflow channels (Ding & Liu 1992; Yamada 1998).

It is also clear that intense rainfall or snowmelt will lead to a rise in the water level of the lake. This cause depends on many factors of which the variability and extremity of the precipitation are perhaps the most significant or, alternatively, the variability and extremity of air temperature in relation to snowmelt (Yamada 1998). If a lake has surface runoff the increasing water level may lead to an increase in the erosion of the outflow channels and to the cycle of “positive feedback” (see above). If a lake does not



**Fig. 2** The former lake basin of Jircacocha in the Cordillera Blanca. Its dam failed after the arrival of a flood wave from lake Palcacocha. The horizontal line indicated by arrows shows the former water level.

have surface runoff then the most important factor is the dam freeboard which is defined as the vertical elevation between the lake level and the lowest point on the dam crest. The rise in lake water level can lead to two different mechanisms of dam destruction. The first mechanism is dam rupture due to the increased hydrostatic pressure. This happens when the hydrostatic pressure overcomes the lithostatic pressure, which keeps the components of the dam together (Richardson & Reynolds 2000a). The second is dam overflow from which the subsequent erosion may induce dam failure (Kattelmann & Watanabe 1997). The failure of a dam under the Dallier glacier in the Cascade Range provides an example of one that occurred as a result of intense rainfall or snowmelt (O'Connor et al. 2001). It is also well known that intense rainfall also a major trigger for slope movements, which may initiate moraine dam failure.

### 3.2 The long-term causes of moraine-dammed lake failures

The long-term causes of dam destruction are the ice melting of buried ice, the impact of hydrostatic pressure, and the effect of time. It is difficult to accurately

constrain which of these long-term issues ultimately leads to the destruction of the dam. This led Yamada (1998) to group these under the title of “self-destruction” due to the absence of an initial external dynamic event (Yamada 1998; Bajracharya et al. 2007b). The long-term causes also weaken the resistance of the dam to dynamic causes: while the impact of hydrostatic pressure and the effect of time have some influence on the moraine dam they are not often the main cause of dam destruction. The degradation of a moraine dam is a function of time and this function does not constitute a single process. It is, instead, a group of processes that may lead to the degradation of a dam over a protracted period and which affects the moraine slope stability, dam freeboard, internal structure etc. In combination with, for example, intense rainfall, the effect of time may lead to mass movements on moraine slopes (Awal et al. 2010). If a lake is associated with a surface outflow, its sequential erosion may cause the lake to empty, without a significant GLOF (Yamada 1998). If a lake is not associated with a surface outflow, the internal erosion of outflow channels through piping may also cause the lake to empty, without a significant GLOF (Clauge & Evans 2000; Haeberli et al. 2001).



**Fig. 3** An example of an uncovered ice lens in the protruding basal moraine of the developing lake Llaca in the Cordillera Blanca.

The term “buried ice” describes an ice lens integrated into the body of the moraine dam (Figure 3). It is possible for this to represent up to 90% of the dam volume (Costa & Schuster 1988). The melting of this buried ice weakens the stability of the dam as it disrupts its structural integrity and may also decrease the dam freeboard (Richardson & Reynolds 2000b; Huggel et al. 2002). The disruption of the structural integrity of the dam enables rupture by hydrostatic pressure while it also decreases the ability of the dam to withstand other causes that would not normally represent a significant problem. For example, the long-term degradation of the moraine dam leads to a decrease in the freeboard which, in combination with moderate rainfall or snowmelt, may lead to dam destruction.

The hydrostatic pressure is the pressure exerted by the gravitational force acting on a water column at certain depth. The water dammed in a moraine-dammed lake affects the dam by this pressure and its long-term affect may lead to the dam failure (Yamada 1998). This cause becomes especially significant if the moraine dam is weakened by, for example, buried ice melting while deep lakes are more susceptible to rupture caused by hydrostatic pressure. The destruction caused by the systematic effect of hydrostatic pressure occurs when the moraine dam is no longer able to resist the hydrostatic pressure, i.e. the hydrostatic pressure exceeds the lithostatic pressure (Richardson & Reynolds 2000a). This may be caused by an increase in the lake water level or the protracted degradation of the moraine dam (Yamada 1998; Jaboyedoff et al. 2004 in Vilímek et al. 2005a). The increase in lake water level may be caused by intense rainfall or snowmelt or the blocking of underground outflow channels (Costa & Schuster 1988; Grabs & Hanish 1993; Janský et al. 2006). It is also possible to increase the hydrostatic pressure by basal ice melting and lake deepening (Watanabe & Rothacher 1996). In cases where dam degradation occurs as a result of buried ice melting, intense slope erosion, or changes in the internal structure of the dam, rupture by hydrostatic pressure may occur without a significant change in the pressure (Richardson & Reynolds 2000a). These all represent examples of “dam self-destruction” and may occur without a dynamic trigger. This happened in 1994 at lake Lugge Tsho in Bhutan (Watanabe & Rothacher 1996). The impact of hydrostatic pressure has a specific position in the categorisation of mechanisms of dam destruction as both dynamic and long-term causes can lead to dam rupture caused by hydrostatic pressure (Figure 1).

#### 4. The comparative analysis

The comparative analysis investigates historical moraine-dammed lakes failures between 1900 and 2009 from three regions: the Cordillera Blanca of Peru, the North American Cordillera, and Himalaya. The basic characteristics of these regions are listed in Table 1. These regions are commonly characterised by glacier retreat at present which is leading to the formation and

**Tab. 1** The basic characteristics of the studied regions.

Region	Mountains	Coordinates	Highest peak(s)	Climatic settings
Cordillera Blanca	Cordillera Blanca (Peru) Cordillera Huayhuash (Peru)	8°–10° S 77°–78° W	Huascarán (6768 m asl)	Tropical High Mountain Climate – Wet & Dry Seasons
North American Cordillera	Coast Mountains (CAN) Rocky Mountains (CAN) Cascade Range (USA)	30°–50° N 120°–135° W	Mt. Waddington (4019 m asl) Mt. Rainier (4392 m asl)	Temperate High Mountain Climatic Zone – 4 Seasons
Himalaya	Himalaya (China, India, Nepal, Bhutan)	27°–35° N 75°–95° E	Mt. Everest/ Sagarmatha (8848 m asl)	Temperate High Mountain Climatic Zone – 4 Seasons

development of new potentially dangerous moraine-dammed lakes. The threat of GLOFs in these areas is real while the downstream valleys are often settled.

#### 4.1 The spatial analysis

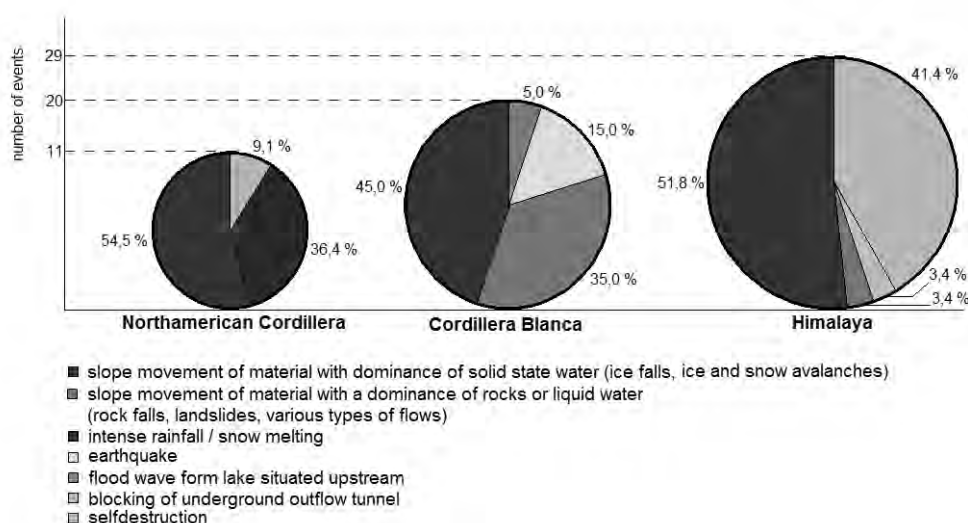
It is important to assess whether there are differences regarding the causes of moraine-dammed lake failures across the three study regions. The slope movements have been divided into two subgroups for this purpose: the first incorporates slope movements in which the displaced material was dominated by solid-state water (ice falls, ice avalanches, and snow avalanches) while the second incorporates movements in which the displaced material was dominated by rock or liquid-state water (rock falls, landslides, and various types of flows). It should be noted that the failure mechanisms for these two subgroups are identical. Furthermore, the concept of dam failure stemming from a combination of long-term causes without an evident dynamic cause ("dam self-destruction" (Yamada 1998) suggests that it will always be difficult to define the precise cause of failure (i.e. there is no distinguishing between the ice melting of buried ice, the impact of hydrostatic pressure, and the effect of

time). Indeed, unless a lake is continuously monitored, it is often difficult to determine the cause of a contemporary GLOF, and even more so in the case of historical events. Therefore, while a single cause may be the most commonly ascribed, there is a possibility that it in part reflects the ease with which it can be identified. The comparison of dynamic and long-term causes (Table 2) shows that, across all three regions, dynamic causes prevail over long-term causes by a ratio of 4 : 1. There are, however, significant regional differences. In the Cordillera Blanca all of the twenty dam failures resulted from a dynamic event while more than two-fifths resulted from a long-term cause in Himalaya ("dam self-destruction").

The most frequent cause of failure in three regions of interest was found to be slope movements in which the displaced material was dominated by solid-state water (ice falls, ice avalanches, and snow avalanches) (Figure 4). This finding corresponds with those of previous studies (e.g. Costa & Schuster 1988; Ding & Liu 1992; Clauge & Evans 2000; Jiang et al. 2004; Awal et al. 2010). The second and the third most frequent causes tend to show distinct regional patterns with the second most common cause being slope movements dominated by solid rock or water in the Cordillera Blanca of Peru, intensive rainfall

**Tab. 2** The dynamic and long-term causes of moraine-dammed lake failures (60 instances where causes of the moraine dam failures are known).

Region	Dynamic Causes		Long-term Causes		Total number of events
	Number of events	%	Number of events	%	
Cordillera Blanca	20	100.0	0	0.0	20
North American Cordillera	10	90.9	1	10.1	11
Himalaya	17	58.6	12	41.4	29
Total	47	78.3	13	21.7	60



**Fig. 4** A representation of the causes of moraine-dammed lake failures in the Cordillera Blanca, the North American Cordillera, and Himalaya.

or snowmelt in the North American Cordillera, and self-destruction in Himalaya. It is of interest to note that intensive rainfall or snowmelt is only recorded as a trigger in the North American Cordillera and it may be that this reflects the particular climatic setting of the region. The moraine-dammed lakes in the North American Cordillera are situated between 1400 and 2400 m asl (O'Connor et al. 2001) whereas in the Cordillera Blanca and Himalaya they generally occur between 4000 and 5000 m asl (Lliboutry et al. 1977; Yamada 1998). The intensity of the combined rainfall and snowmelt may be greater in the North American Cordillera during the summer due to these lower elevations. Thereafter, only one moraine-dammed lake failure in the North American Cordillera was attributed to dam self-destruction.

The trigger of dam self-destruction represents the second most frequent cause of moraine dam failures in Himalaya. This may reflect the significant volumes of buried ice that occur in many moraine dam bodies in this region (Yamada 1998; Bajracharya et al. 2007b). The melting of buried ice leads to degradation of moraine dam and this may lead to its failure, especially in combination with the affect of hydrostatic pressure impact, without a dynamic triggering event (see above). Thereafter, one moraine dam failure in the region was caused by the blocking of underground outflow channels and one by a slope movement into a lake in which the displaced material was dominated by rock or liquid-state water. The second most frequent cause of moraine-dammed lake failures in the Cordillera Blanca were slope movements into lakes in which the displaced material was dominated by rock. In fact, slope movements account for 80% of all moraine dam failures in this region while 15% could

be attributed to an earthquake. Thereafter, one dam failure was caused by the propagation of a flood wave which resulted from the failure of an upstream dam.

#### 4.2 The temporal analysis

This section focuses on the temporal distribution of 66 moraine-dammed lake failures and GLOFs over months (Figure 5) and 75 moraine-dammed lake failures and GLOFs over years (Figure 6). The monthly differences in the distribution of GLOFs shown in Figure 5 clearly reflect the general climatic setting of each of the study regions. The temporal distribution of moraine dam failures is similar in the North American Cordillera and Himalaya as dam failures occur exclusively during the summer season from June to September. The lake water levels are higher at this time because the warmer temperatures melt glacial ice and, thereby, reduce the dam freeboard. In the Cordillera Blanca, with its alternating wet and dry seasons, moraine dam failures are more evenly distributed but cluster during the wet season from December to May. The lake water levels are again higher at this time because there is a considerable amount of precipitation while the temperatures are also slightly warmer than they are during the dry season. These data indicate that the moraine dam failures occur most commonly during the warmer times of the year and corroborate the notion the most frequent cause of moraine dam failures are dynamic slope movements in which the displaced material was dominated by solid-state water (ice falls, ice avalanches, and snow avalanches).

The annual distribution of moraine dam failures has been analysed using a dataset of seventy-five events

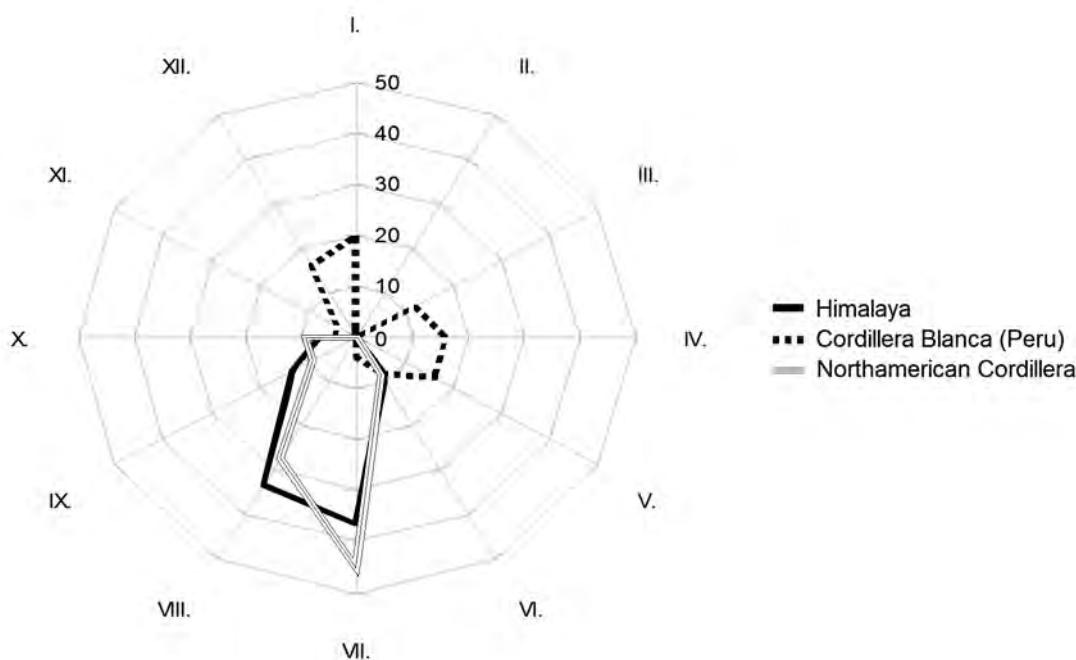


Fig. 5 The distribution of moraine dam failures plotted according to month (66 instances overall).

for which the year of failure is known. In the period between 1900 and 1924 only one moraine-dam failure was recorded – this occurred at lake Zhanlonba in China during 1902 (Ding & Liu 1992) (Figure 6). In the period between 1935 and 1944 eight moraine-dam failures were recorded in the Cordillera Blanca region. These events claimed thousands of lives and caused considerable damage to infrastructure as well as leading to a series of investigations into moraine-dammed lakes (Zapata 2002; Carey 2005). These investigations called for remedial work at thirty-five sites in the form of artificial dams, concrete outlets, tunnels, etc. (Reynolds 2003; Carey et al. 2012). It may also be one of the reasons for the decreased number of moraine dam failures in the following years. In the period between 1970 and 1974 five failures were recorded in the region. These were all triggered by the catastrophic earthquake that occurred in Cordillera Blanca on 31st May 1970. The next moraine dam failure did not occur for another twenty-seven years. This protracted period of stability is thought to reflect the extensive remedial works and rupture of the most unstable lake dams following the earthquake in 1970. The annual distribution of moraine dam failure in Himalaya is more regular with at least two failures in each five-year period between 1955 and 2004. There was a maximum of six failures in the five-year period between 1980 and 1984. The annual distribution of moraine dam failures in the North American Cordillera is also broadly constant with no peaks evident.

## 5. Discussion

There are a number of published lists of moraine-dammed lake failures for specific regions such as those that have been compiled for the Cordillera Blanca (Zapata 2002), the North American Cordillera (Clague & Evans 2000; O'Connor et al. 2001), and Himalaya (Yamada 1998; Ives et al. 2010). These lists have been updated and supplemented with as much data as it was possible to attain. There is, however, a paucity of events both at the beginning and at the end of the period from 1900 to 2009. The paucity of events at the beginning of this period may reflect an absence of moraine-dammed lake failures at that time or, more likely, that such events were not recorded if the areas in which they occurred were uninhabited or if no significant damage occurred. The paucity of events at the end of this period may again reflect an absence of moraine-dammed lake failures but is more likely to reflect the amount of time it takes for the data to be processed and published. In a number of instances the cause of the moraine-dammed lake failure is not known with certainty and it is only possible to attribute a probable cause. It is, nonetheless, evident that the most common causes are slope movements in which the displaced material is dominated by solid-state water (ice falls, ice avalanches, and snow avalanches). This finding corresponds with those of previous studies (e.g. Costa & Schuster 1988; Ding & Liu 1992; Clague & Evans 2000; Jiang et al. 2004; Awal et al. 2010).

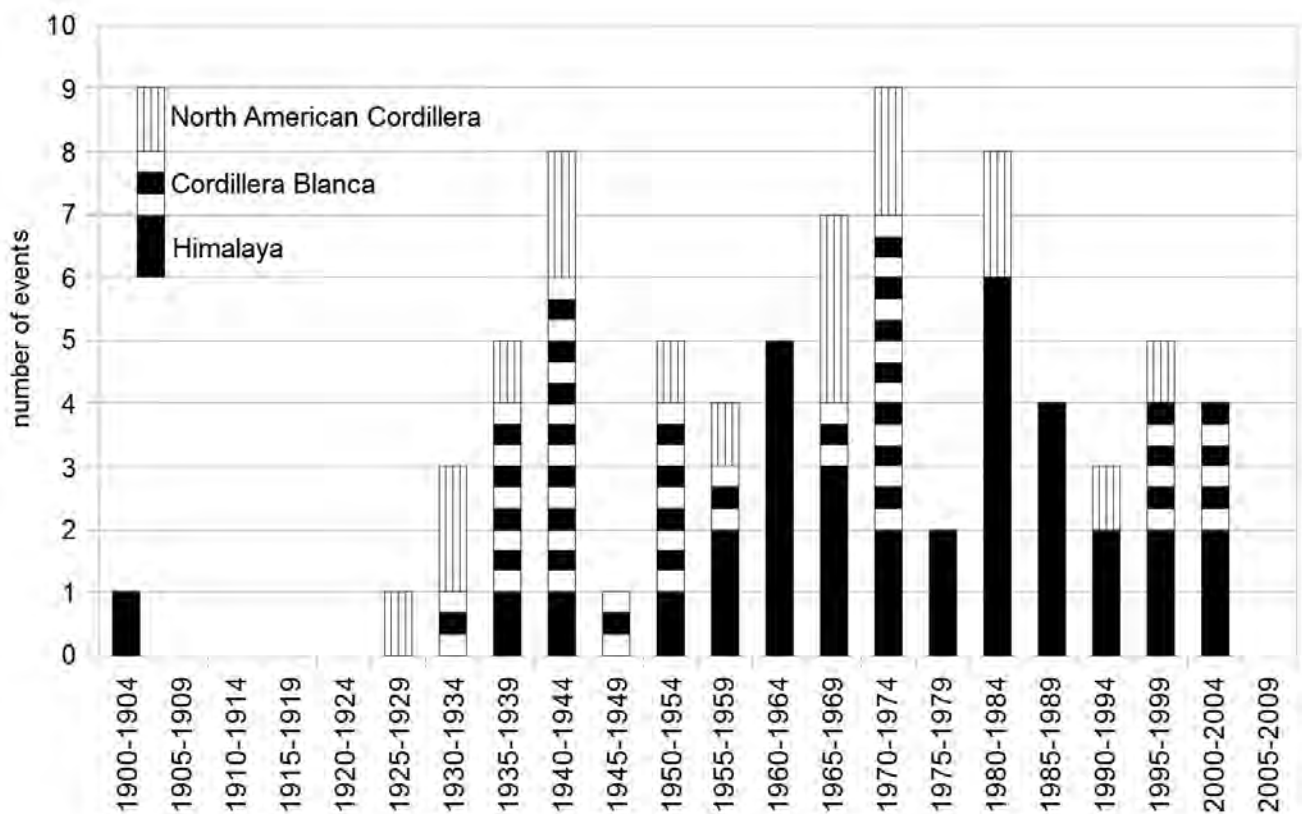


Fig. 6 The distribution of moraine dam failures plotted according to year (75 instances overall).



## 6. Conclusions

There are eight main causes, of which five are characterised as dynamic and three as long-term, and these are associated with around twenty failure mechanisms. The dynamic causes are slope movements into the lake (e.g. icefalls, avalanches, rockfalls, landslides, and other types of flow), earthquakes, a flood wave from a lake situated upstream, blocking of underground outflow channels, and intensive rainfall or snowmelt. The long-term causes are the ice melting of buried ice, the impact of hydrostatic pressure, and the effect of time. It is, therefore, clear that GLOFs are associated closely to various types of natural hazard. The similarities and disparities between the particular causes were investigated as well as the temporal characteristics of events in the Cordillera Blanca of Peru, the North American Cordillera, and Himalaya. It was found that dynamic causes are around four times more common than long-term causes although significant regional differences are seen: in the Cordillera Blanca of Peru all dam failures resulted from a dynamic event while more than two-fifths resulted from a long-term cause in Himalaya. The most frequent causes of GLOFs from moraine-dammed lakes were found to be slope movements in which the displaced material was dominated by solid-state water (ice falls, ice avalanches, and snow avalanches). This accounted for around half of all events irrespective of the specific study area. The other causes tended to show distinct regional patterns with the second most common cause being slope movements dominated by solid rock or water in the Cordillera Blanca of Peru, intensive rainfall or snowmelt in the North American Cordillera, and self-destruction in Himalaya. The temporal distribution of moraine dam failures is similar in the North American Cordillera and Himalaya as dam failures occur exclusively during the summer season from June to September while in the Cordillera Blanca they are more evenly distributed but cluster during the wet season from December to May. These patterns clearly reflect the general climatic setting of each of the study regions. The annual distribution of these failures is broadly constant with no particular trends yet evident. The recognition of these regional differences is necessary in order to build optimal regionally focused methods for moraine-dammed lakes hazard assessment in the future.

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## REFERENCES

- AWAL, R., NAKAGAWA, H., FUJITA, M., KAWAIKE, K., BABA, Y., ZHANG, H. (2010): Experimental study on glacial lake outburst floods due to waves overtopping and erosion of moraine dam. *Annals of Disaster Prevention Research Institute* 53, 583–594.
- BAJRACHARYA, B., SHRESTHA, A. B., RAJBHANDARI, L. (2007a): Glacial lake outburst floods in the Sagarmatha region. *Mountain Research and Development* 27, 336–344.
- BAJRACHARYA, S. R., MOOL, P. K., SHRESTHA, B. R. (2007b): The impact of global warming on the glaciers of the Himalaya. In: *International Symposium on Geo-disasters, Infrastructure Management and Protection of World Heritage Sites 25–26 Nov 2006*. Kathmandu: International Centre for Integrated Mountain Development (ICIMOD), 231–242.
- BENN, D. I., EVANS, D. J. A. (1998): *Glaciers & Glaciation*. London, Hodder Education.
- BOLCH, T., BUCHROITHNER, M. F., PETERS, J., BASSLER, M., BAJRACHARYA, S. (2008): Identification of glacier motion and potentially dangerous glacial lakes in the Mt. Everest region/Nepal using spaceborne imagery. *Natural Hazards and Earth System Sciences* 8, 1329–1340.
- BOLCH, T., PETERS, J., YEROGOV, A., PRADHAN, B., BUCHROITHNER, M., BLAGOVESHCHENSKY, V. (2001): Identification of potentially dangerous glacial lakes in the northern Tien Shan. *Natural Hazards* 59, 1691–1714.
- BREIEN, H., DE BLASIO, F. V., ELVERHØI, A., HØEG, K. (2008): Erosion and morphology of a debris flow caused by a glacial lake outburst flood, Western Norway. *Landslides* 5, 271–280.
- CAREY, M. (2005): Living and dying with glaciers: people's historical vulnerability to avalanches and outburst floods in Peru. *Global and Planetary Change* 47, 122–134.
- CAREY, M., FRENCH, A., O'BRIEN, E. (2012): Unintended effects of technology on climate change adaptation: an historical analysis of water conflicts below Andean Glaciers. *Journal of Historical Geography* 38, 181–191.
- CAREY, M., HUGGEL, C., BURY, J., PORTOCARRERO, C., HAEBERLI, W. (2011): An integrated socio-environmental framework for glacial hazard management and climate change adaptation: lessons from Lake 513, Cordillera Blanca, Peru. *Climatic Change* 112, 733–767.
- CENDERELLI, D. A., WOHL, E. E. (2001): Peak discharge estimates of glacial-lake outburst floods and “normal” climatic floods in the Mount Everest region, Nepal. *Geomorphology* 40, 57–90.
- CLAUGE, J. J., EVANS, S. G. (2000): A review of catastrophic drainage of moraine-dammed lakes in British Columbia. *Quaternary Science Reviews* 19, 1763–1783.
- COSTA, J. E., SCHUSTER, R. L. (1988): The formation and failure of natural dams. *Geological Society of America Bulletin* 100, 1054–1068.
- DING, Y., LIU, J. (1992): Glacial lake outburst flood disasters in China. *Annals of Glaciology* 16, 180–184.
- DUSSAILLANT, A., BENITO, G., BUYTAETR, W., CARLING, P., MEIER, C., ESPINOZA, F. (2010): Repeated glacial-lake outburst floods in Patagonia: an increasing hazard? *Natural Hazards* 54, 469–481.
- EMMER, A., VILÍMEK, V. (2013): Hazard assessment of GLOFs for moraine-dammed lakes: an example from Cordillera Blanca, Peru. *Natural Hazards and Earth System Sciences*, 13, 1551–1565.
- EVANS, S. G., CLAUGE, J. J. (1994): Recent climatic change and catastrophic geomorphic processes in mountain environments. *Geomorphology* 10, 107–128.

- EVANS, S. G., CLAUGE, J. J., HUNGR, O., GEERTSEMA, M. (2002): Climate change and geomorphological hazards in the Canadian Cordillera; the anatomy of impacts and some tools for adaptation, Climate Change Action Fund Project A099. Scientific Report 1999–2001: Summary of Activities and Results. GLOFs DATABASE (2012): <glofs-database.com>. Last accessed: 10/2012.
- GRABS, W. E., HANISCH, J. (1993): Objectives and prevention methods for glacier lake outburst floods (GLOFs). In: Snow and Glacier Hydrology (Proceedings of the Kathmandu Symposium, November 1992), Great Yarmouth (UK), 341–352.
- HAEBERLI, W., KÄÄB, A., MÜHLL, D. V., TEYSSEIRE, P. (2001): Prevention of outburst floods from periglacial lakes at Grubengletscher, Valais, Swiss Alps. *Journal of Glaciology* 47, 111–122.
- HARRISON, S., GLASSER, N., WINCHESTER, V., HARESIGN, E., WARREN, C., JANSSON, K. A. (2006): Glacial lake outburst flood associated with recent mountain glacier retreat, Patagonian Andes. *Holocene* 16, 611–620.
- HEGGLIN, E., HUGGEL, C. (2008): An integrated assessment of vulnerability to glacial hazards – a case study in the Cordillera Blanca, Peru. *Mountain Research and Development* 28, 299–309.
- HEWITT, K. J. (1982): Natural dams and outburst floods of the Karakoram Himalaya. In: *Hydrological Aspects of Alpine and High Mountain Areas* (Proceedings of the Exeter Symposium, July 1982), Great Yarmouth (UK), 259–269.
- HUBBARD, B., HEALD, A., REYNOLDS, J. M., QUINCEY, D., RICHARDSON, S. D., ZAPATA, M. L., SANTILLAN, N. P., HAMBREY, M. J. (2005): Impact of a rock avalanche on a moraine-dammed proglacial lake: Laguna Safuna Alta, Cordillera Blanca, Peru. *Earth Surface Processes and Landforms* 30, 1251–1264.
- HUGGEL, C., HAEBERLI, W., KÄÄB, A., BIERI, D., RICHARDSON, S. (2004): An assessment procedure for glacial hazards in the Swiss Alps. *Canadian Geotechnical Journal* 41, 1068–1083.
- HUGGEL, C., KÄÄB, A., HAEBERLI, W., TEYSSEIRE, P., PAUL, F. (2002): Remote sensing based assessment of hazards from glacier lake outbursts: a case study in the Swiss Alps. *Canadian Geotechnical Journal* 39, 316–330.
- ITURRIZAGA, L. (2005): Historical glacier-dammed lakes and outburst floods in the Karamba valley (Hindukush-Karakoram). *Geo Journal* 63, 1–47.
- IVES, J. D., SHRESTHA, B. R., MOOL, P. K. (2010): Formation of Glacial Lakes in the Hindu Kush-Himalayas and GLOF Risk Assessment. Kathmandu (Nepal), International Centre for Integrated Mountain Development (ICIMOD).
- JABOYEDOFF, M., BAILLIFARD, F., BARDOU, E., GIROD, F. (2004): The effect of weathering on Alpine rock instability. *Quarterly Journal of Engineering Geology and Hydrogeology* 37, 95–103.
- JANSKÝ, B., ENGEL, Z., ŠOBR, M., BENEŠ, V., ŠPAČEK, K., YEROKHIN, S. (2009): The evolution of Petrov lake and moraine dam rupture risk (Tien-Shan, Kyrgyzstan). *Natural Hazards* 50, 83–96.
- JANSKÝ, B., ŠOBR, M., YEROKHIN, S. (2006): Typology of high mountain lakes of Kyrgyzstan with regard to the risk of their rupture. *Limnological Review* 6, 135–140.
- JIANG, Z. X., CUI, P., JIANG, L. W. (2004): Critical hydrological conditions for overflow burst of moraine lake. *Chinese Geographical Science* 14, 39–47.
- KATTELMANN, R., WATANABE, T. (1997): Draining Himalayan glacial lakes before they burst. In: *Destructive Water: Water-Caused Natural Disasters, their Abatement and Control* (Proceedings of the Conference held at Anaheim, California, June 1996), 337–343.
- KERSHAW, J. A., CLAUGE, J. J., EVANS, S. G. (2005): Geomorphic and sedimentological signature of a two-phase outburst flood from moraine-dammed Queen Bess Lake, British Columbia, Canada. *Earth Surface Processes and Landforms* 30, 1–25.
- KLIMEŠ, J. (2012): Geomorphology and natural hazards of the selected glacial valleys, Cordillera Blanca, Peru. *AUC Geographica* 47, 25–31.
- LLIBOUTRY, L., MORALES, B. A., PAUTRE, A., SCHNEIDER, B. (1977): Glaciological problems set by the control of dangerous lakes in Cordillera Blanca, Peru. I. Historical failures of moraine dams, their causes and prevention. *Journal of Glaciology* 18, 239–254.
- NARAMA, C., DUSHONAKUNOV, M., KÄÄB, A., DAIYROV, M., ABDRAKHMATOV, K. (2010): The 24 July 2008 outburst flood at the western Zyndan glacier lake and recent regional changes in glacier lakes of the Teskey Ala-Too range, Tien Shan, Kyrgyzstan, *Natural Hazards and Earth System Sciences* 10, 647–659.
- O'CONNOR, J. E., HARDISON, J. H., COSTA, J. E. (2001): Debris flows from failures of Neoglacial-age moraine dams in the Three Sisters and Mount Jefferson Wilderness areas, Oregon. Reston (Virginia): U. S. Geological Survey.
- PETRAKOV, D. A., KRYLENKO, I. V., CHERNOMORETS, S. S., TUTUBALINA, O. V., KRYLENKO, I. N., SAKHMINA, M. S. (2007): Debris flow hazard of glacial lakes in the Central Caucasus. In: Chen & Major (eds.) *Debris-Flow Hazards Mitigation: Mechanics, Prediction, and Assessment*. Millpress, Netherlands, 703–714.
- PLAFKER, G., EYZAGUIRRE, V. R. (1979): Rock avalanche and wave at Chungar, Peru. In: *Rockslide and Avalanches*. Elsevier, 269–279.
- REYNOLDS, J. M. (2003): Development of glacial hazard and risk minimisation protocols in rural environments: methods of glacial hazard assessment and management in the Cordillera Blanca, Peru. Flintshire (UK), Reynolds Geo-Sciences Ltd.
- RICHARDSON, S. D., REYNOLDS, J. M. (2000a): An overview of glacial hazards in the Himalayas. *Quaternary International* 65–66, 31–47.
- RICHARDSON, S. D., REYNOLDS, J. M. (2000b): Degradation of ice-cored moraine dams: implications for hazard development. In: *Debris-Covered Glaciers* (Proceedings of a workshop held at Seattle, Washington, USA, September 2000), 187–197.
- SHRESTHA, A. B. (2010): Managing flash flood risk in Himalaya-information sheet # 1/10. Kathmandu (Nepal), International Centre for Integrated Mountain Development (ICIMOD).
- STRASSER, M., SCHINDLER, C., ANSELMETTI, F. S. (2008): Late Pleistocene earthquake-triggered moraine dam failure and outburst of Lake Zurich, Switzerland. *Journal of Geophysical Research* 113, 1–16.
- VILÍMEK, V., KLIMEŠ, J., ZAPATA, M. L. (2005a): Glacial lake outburst flood in the areas of Huarás, Cordillera Blanca, Peru. *Studia Geomorphologica Carpatho-Balcanica* 39, 115–124.
- VILÍMEK, V., ZAPATA, M. L., KLIMEŠ, J., PATZELT, Z., SANTILLAN, N. (2005b): Influence of glacial retreat on natural hazards of the Palcacocha Lake area, Peru. *Landslides* 2, 107–115.
- VUICHARD, D., ZIMMERMANN, M. (1987): The 1985 catastrophic drainage of a moraine-dammed lake, Khumbu Himal, Nepal: cause and consequences. *Mountain Research and Development* 7, 91–110.
- WATANABE, T., ROTHACHER, D. (1996): The 1994 Lugge Tsho glacial lake outburst flood, Bhutan Himalaya. *Mountain Research and Development* 16, 77–81.

- YAMADA, T. (1998): Glacier Lake and its Outburst Flood in the Nepal Himalaya. Tokyo, Japanese Society of Snow and Ice.
- ZAPATA, M. L. (1984): Avalanchas y aluviones en la departamento de Ancash, Huaráz (Peru), Electroperú, S. A.
- ZAPATA, M. L. (2002): La dinamica glaciár en lagunas de la Cordillera Blanca. Acta Montana 19, 37–60.

## RÉSUMÉ

### **Analýza příčin a mechanismů destrukcí hrází jezer hrazených morénami v pohoří Cordillera Blanca (Peru), Severoamerická Kordillera a Himaláj**

Příspěvek je členěn do dvou částí. První část má rešeršní charakter a shrnuje rozličné příčiny a mechanismy destrukcí (protržení) hrází jezer hrazených morénami. Pět dynamických

příčin (různé typy svahových pohybů, zemětřesení, povodňová vlna z výše položeného jezera, intenzivní dešťové srážky / tání sněhu, ucpání podzemních odtokových kanálů) a tři dlouhodobé příčiny (odtávání pohřbeného ledu, působení hydrostatického tlaku a dlouhodobá degradace tělesa hráze v čase) jsou popsány spolu s mechanismy vedoucími k destrukcím morénových hrází, a to včetně konkrétních příkladů ze zájmových oblastí. Ve druhé části příspěvku je provedena srovnávací analýza těchto událostí mezi oblastmi pohoří Cordillera Blanca (Peru), Severoamerická Kordillera a pohoří Himaláj. Na základě vytvořené databáze protržených morénových hrází mezi lety 1900 a 2009 je zhodnoceno jednak zastoupení různých příčin, jednak časová distribuce těchto událostí. Nejfrekventovanější příčinou ve všech studovaných oblastech byl dynamický svahový pohyb do jezera. Zastoupení a výskyt dalších příčin se však mezi jednotlivými oblastmi výrazně liší. Časová distribuce událostí výrazně odlišuje oblast Cordillera Blanca od zbývajících dvou, což do určité míry odráží roční chod klimatu a na něj vázaných příčin destrukcí morénových hrází.

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