Glacier Retreat, Lakes Development and Associated Natural Hazards in Cordilera Blanca, Peru

Adam Emmer, Vít Vilímek, Jan Klimeš and Alejo Cochachin

Abstract Cordillera Blanca is the heaviest glacierized tropical range in the world. Due to the global climate change, most of glaciers are retreating and thinning. Glacier retreat leads to the formation and development of all types of potentially hazardous glacial lakes (bedrock-dammed, moraine-dammed, and ice-dammed). Potential hazardousness of glacial lakes is strongly interconnected with dynamic slope movements: (1) sudden release of water from glacial lakes (also known as glacial lake outburst floods—GLOF) is mainly caused by dynamic slope movement into the lake (about 80 % in the Cordillera Blanca); (2) released water may easily transform into debris-flow or mud-flow, thanks to its high erosion and transport potential. Based on field study and remotely sensed images, this contribution documents glacier retreat in the Cordillera Blanca with regards to formation and development of new potentially hazardous glacial lakes, which evolve mainly in elevations of about 4,600–5,000 m a.s.l. We introduce and describe three hazardous events associated with glacier retreat in the last decade: (a) sudden release of water from moraine-dammed Lake Palcacocha in 2003; (b) sudden release of water from bedrock-dammed lake No. 513 in 2010; and (c) sudden release of water from bedrock-dammed Lake Artizon Alto and

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subsequent moraine dam failure of downstream situated Lake Artizon Bajo in 2012. The first and third events were caused by landslides of lateral moraines (which are often non-consolidated and nearly vertical) into the lakes. The second event was caused by ice- and rockfall into the lake. These events illustrate that various natural hazards (dynamic slope movements, floods) associated with glacier retreat in the Cordillera Blanca are closely linked and represent actual threats to urbanization and safety of lives and property.

Keywords Natural hazards · Glacier retreat · Dynamic slope movements · GLOFs · The Cordillera Blanca

1 Introduction

Impact of climate change to glacier retreat and thinning (downwasting) and associated natural hazards in high mountain areas has been described by O'Connor and Costa (1993) and more recently, by Clague et al. (2012). Glacier retreat is closely tied with various types of natural hazards which have potential to cause significant damages. These include direct and indirect dynamic slope movements (Richardson and Reynolds 2000a), catastrophic floods following sudden water release from any type of high mountain lake (Costa and Schuster 1988), earthquakes following intense ice loss (deglaciation-induced earthquakes) (Harrison et al. 2006), and also, changes in runoff regime followed by droughts (Mark 2002). These apparently disparate natural hazards are in fact naturally linked. Based on remotely sensed photographs and field study conducted in 2010, 2011 and 2012, this contribution brings three examples of ties (links) among glacier retreat, selected glacial lake development (Fig. 1), various types of dynamic slope movements and outburst floods in the Cordillera Blanca mountain range (Peru).

Richardson and Reynolds (2000a) distinguishes between direct and indirect dynamic slope movements associated with deglaciation. Direct dynamic slope movements associated with deglaciation are snow/ice avalanches, while indirect are mass re-organizing paraglacial processes affecting steep sided valleys—e.g. rock avalanches and landslides. This phenomenon of indirect dynamic slope movements associated with deglaciation is also called "landslide response to post-Little Ice Age glacier retreat and thinning" (Holm et al. 2004). Together, these two groups of dynamic slope movements represent the most frequent trigger of sudden and often catastrophic water release from glacial lakes in the Cordillera Blanca—80 % overall of which 45 % are direct and 35 % indirect dynamic slope movements into the lake. The remaining 20 % of sudden water release from glacial lakes in the Cordillera Blanca are due to earthquakes and flood waves from lakes situated upstream (Emmer and Cochachin 2013). A sudden water release from any type of glacial lake irrespective of its cause is called a "Glacial lake outburst

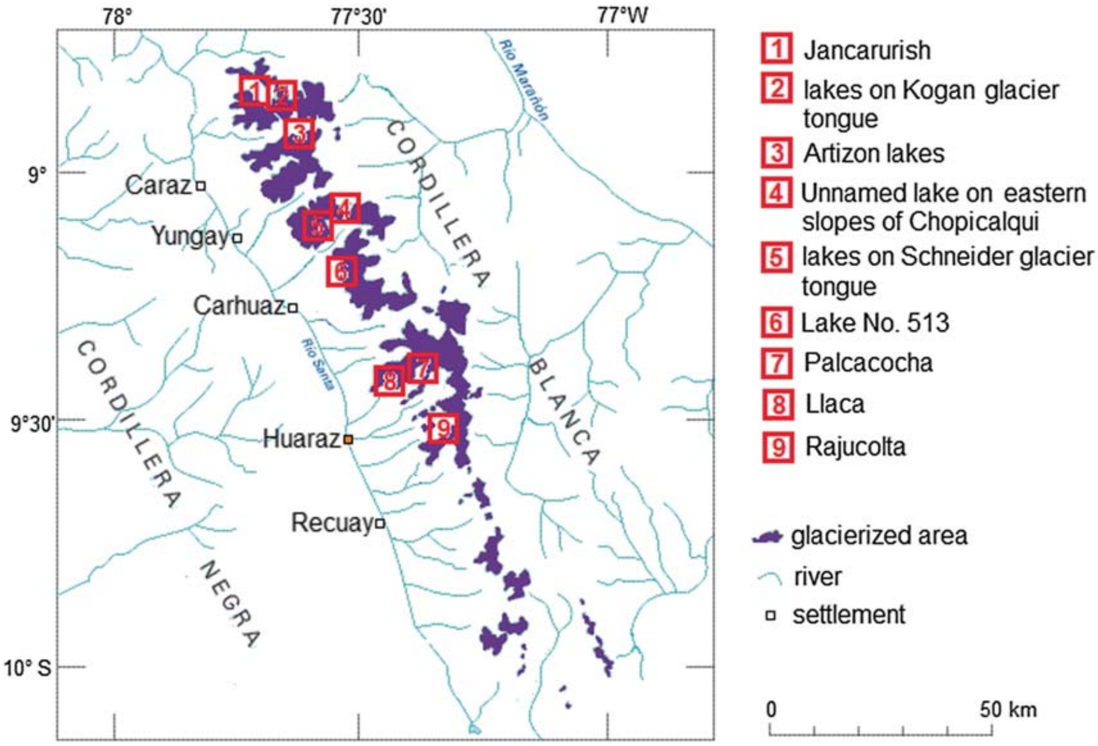

Fig. 1 The Cordillera Blanca and the location of lakes mentioned in this paper (*base map* USGS)

flood" (GLOF). A GLOF may result from failure or overflow of a glacial lake dam and, thanks to its high erosion and transport potential, may easily transform into flow movement (e.g. debris-flow or mud-flow). These events claimed thousands of lives during the 20th century, and caused significant damage in the Cordillera Blanca. The most catastrophic was the moraine-dam failure of lake Palcacocha in 1941 and the moraine-dam failure of lake Jancarurish in 1950 (Zapata 2002).

2 Study Area: The Cordillera Blanca

The Cordillera Blanca is located in the northcentral Andes, in the Ancash region of Peru (8.5°–10°S; 77°–78°W). This mountain range is part of the Cordillera Occidental (Western Cordillera). The Cordillera Blanca is the highest Peruvian mountain range with sixteen peaks over 6 000 m a.s.l. and also the most heavily glacierized tropical range in the world, with present glacier extent of about 600 km^2 (Georges 2004). This figure represent approximately one fourth of worldwide extent of tropical glaciers (Ames and Francou 1995). The western part of the Cordilllera Blanca is drained by Rio Santa into the Pacific Ocean, while the eastern part is drained by Rio Marañon and then by the Amazon River into the Atlantic Ocean (Fig. 1). The geological structure is very complicated and differs from south to north as well as from east to west. The upper parts of the Cordillera Blanca are underlain by granitic intrusions, but there are also parts which are underlain by extrusive vulcanic rocks such as andesitic rocks and tuffs or sedimentary rocks such as sandstones and shales (Wilson et al. 1995). The Cordillera Blanca is an active seismic region, where large earthquakes occur (e.g. 1970 earthquake with M7.7), cause significant damages and also initiate various types of natural hazards such as dynamic slope movements or GLOFs (Lliboutry et al. 1977). The main fault zone extends approximately 210 km through the western slopes of this range.

2.1 Glacier Retreat

The Cordillera Blanca had been glacierized several times in geologic history and the glacier extent was much more extensive during the late Pleistocene and Holocene (Mark 2002; Vilímek 2002). Clear evidence of past glacier extent such as massive moraines, U-shaped valleys and striations can still be found in reliefs, kilometers away from the present position of glaciers. The last significant glacier advance happened during the so called "Little Ice Age"—a relatively cold period, which culminated (according to lichenometric dating and ice-core data from Huascarán glacier) from 1590 to 1720 and less extensively from 1780 to 1880 (Thompson et al. 2000; Solomina et al. 2007). Since the end of the Little Ice Age, glaciers started to retreat and new glacial lakes began to form and develop.

Moraines that formed during the Little Ice Age mark the maximal glacier extent during this period, but there is no appropriate evidence for the subsequent glacier retreat during the 19th Century. Glaciers of the Cordillera Blanca have been inventoried several times in the 20th Century and the trend of retreat and thinning is obvious. Georges (2004) reconstructed the extent of glaciers in the 1930s to 800–850 km^2, based on the first aerial photographs of this region. According to remotely sensed photographs of this area in the 1970s, the extent of glaciers decreased in 40 years to 723 km^2 (Ames and Francou 1995). The latest investigation demonstrated that the extent of glaciers was about 600 km^2 at the beginning of the 21st Century (Georges 2004). These numbers show that glacier extent has decreased by about one fourth since the 1930s. The total volume of glaciers can also be assumed to have decreased in this period, due to downwasting. This intense glacier retreat and thinning is visible on all glaciers within the Cordillera Blanca; nevertheless, there are some differences in the rates of glacier retreat. Areal and volumetric glacier retreat is mostly controlled by various combinations of the following factors:

1. Meteorological regime—solar radiation—energy for glacier thawing is mostly gained from solar radiation, thus a very important characteristic is the total number of hours of sunshine in a year and aspect of slopes and its exposition (see below) (Oerlemans and Knap 1998; Mark 2002)
    - temperatures and precipitation (e.g. Huggel et al. 2004)—every part (valley) of the Cordillera Blanca has a specific meteorological regime, but in general,

sites with higher temperatures and/or lower precipitation have greater rates of glacier retreat

2. Topographic setting—aspect—aspect is generally considered as one of the most important non-climatic characteristics influencing rate of glacier retreat, because it is closely connected with hours of solar radiation. Glaciers with an eastern aspect have the highest rate of glacier retreat within the Cordillera Blanca, while glaciers with southwestern aspect have lower rates of glacier retreat (Mark 2002)
   - exposure—exposition is a second topographical characteristic, which controls rate of solar radiation. That is, sites which are often shaded by surrounding terrain receive less solar radiation than exposed sites.
3. Glacier characteristics—area (volume) of glacier—Larger glaciers have a greater volume of ice and lower initial rates of retreat and thinning; larger ice bodies are able to resist for a long time (Kaser 1995)
   - debris coverage—the role of debris cover on glacier retreat is not uniform. On one handglacier tongues covered by a thick debris layer are able to resist the direct impact of solar radiation and thus may persist for a longer time in lower altitudes (in the form of buried ice). On the other hand glacier tongues covered by a thin debris layer thin easily, due to heat exchange between the ice body and dark debris with a higher heat capacity and lower albedo (Richardson and Reynolds 2000b).

The number of glacial lakes in the Cordillera Blanca during the 20th Century increased with a decrease in the extent of the glacierized area (Table 1). The first inventory of lakes was presented by Concha (1951) who showed that there were 230 lakes of significant size at the beginning of the 1950s, of which most of the glacial lakes in altitudes between 4,250 and 4,600 m a.s.l. Morales et al. (1979) updated the overall number of lakes of significant size to 267. Portocarrero (1995) summarised 899 lakes in the Cordillera Blanca and now there are more than one thousand of lakes overall (see Table 1), and new lakes form and develop in the altitudes between 4,600 and 5,000 m a.s.l.

Table 1 Decreasing extent of glacierized area and increasing number of lakes since 1930 within the Cordillera Blanca

Years	Glacier extent (km^2)	Number of lakes	References
1930	800–850	–	Georges (2004)
1951	–	230 (lakes of significant size)	Concha (1951)
1970	723	267 (lakes of significant size)	Ames and Francou (1995); Morales et al. (1979)
1995	–	899 (overall)	Portocarrero (1995)
2000	600	–	Georges (2004)
2012	<600	>1,000 (overall)	This study

2.2 Typology of Glacial Lakes

A glacial lake is a lake, whose basin was excavated by glacial erosion, dammed by a glacier body or moraine or some combination of these. A number of typologies of (glacial) lakes for different purposes and regions have been created e.g. by Hutchinson (1957), or later by Kalff (2002) or Janský et al. (2006). Typology of lakes within the Cordillera Blanca with regard to its potential hazardousness was first presented by Concha (1951). One of the most common typologies is one that divides glacial lakes according to the material which forms the lake dam. This typology generally distinguishes between:

1. bedrock-dammed lakes;
2. moraine-dammed lakes; and
3. ice-dammed lakes.

The first and second types easily reach a significant volume of accumulated water (from 10^6 to 10^7 m^3) within the Cordillera Blanca, while the third type does not.

Bedrock-dammed lakes form in depressions excavated by glacial erosion after its retreat. The dam of the lake is composed of solid rocks, and thus is considered to be stable (Huggel et al. 2004). Therefore, dam breach is not a possible scenario for sudden water release, unlike the dam overflow. This type of lake is very common within the Cordillera Blanca, but they are often insignificant in size. Of course, there are some which exceed a volume of 10^6 m^3 (e.g. lake No. 513, lake Auquiscocha or lake Churup), but most of them do not.

Concha (1951) distinguished between bedrock-dammed lakes with direct contact with a glacier and without contact with a glacier, because direct contact with a glacier and the possibility of it calving into the lake and producing displacement waves is a very important characteristic in the potential hazardousness of the selected lake. New bedrock-dammed lakes evolve in present days, some of them evolve in hanging valleys mostly at altitudes ranging between 4,600 and 5,000 m a.s.l. An example of a new, rapidly growing bedrock-dammed lake is an unnamed lake situated beneath the eastern slopes of Chopicalqui massif (6,354 m a.s.l.). This lake enlarged its area between 2003 (Fig. 2a) and 2011 (Fig. 2b) more than two times. The volume of accumulated water, which is available for sudden water release, is also increasing rapidly. The maximum length of the lake was more than 500 m in 2011 and there is a great potential for further growth following glacier retreat.

Moraine-dammed lakes are most frequently formed behind moraines after glacier retreat. This type represents the largest lake in the Cordillera Blanca. The volume of accumulated water may exceed 10^7 m^3. Some examples are Lakes Jancarurish ($12{,}322 \times 10^6$ m^3; Fig. 3a); Rajucolta ($17{,}546 \times 10^6$ m^3; Fig. 3b), and Placacocha ($17{,}325 \times 10^6$ m^3; Fig. 3c), which are all dammed by massive moraines formed during the Little Ice Age at elevations between 4,250 and 4,600 m a.s.l. All these examples of very large contemporary moraine-dammed lakes within the Cordillera Blanca had produced GLOFs in history (Rajucolta in

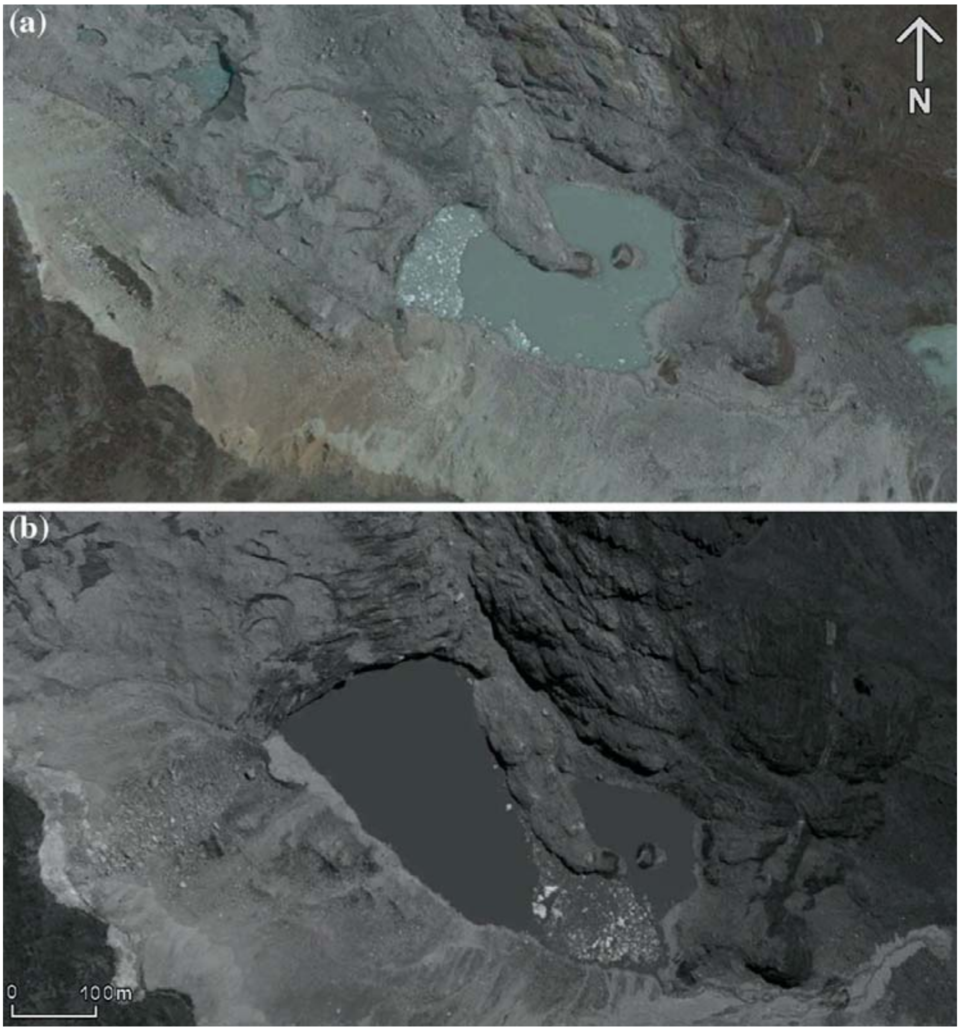

Fig. 2 Unnamed growing bedrock-dammed lake beneath the eastern slopes of Chopicalqui massif. Part **a** was taken in 2003, while part **b** was taken in 2011. Clear evidence for a small outburst flood after overflowing the dam following glacier calving or landslide of lateral moraine into the lake is visible in part **b** (*Source* Google Earth Digital Globe 2013)

1883; Palcacocha in 1941 and 2003; and Jancarurish in 1950) (Zapata 2002). The height of LIA moraine dams may exceed one hundred meters and their slopes are frequently very steep and unstable. Richardson and Reynolds (2000a) showed that lakes formed behind LIA moraines are potentially dangerous because they are dammed by unconsolidated and poorly sorted material which enhances dam failures, and at the same time, they are often in direct contact with the glaciers (icefalls into the lake represent the most frequent trigger for outburst floods). Clague and Evans (2000) showed that moraine-dammed lakes most commonly fail at the beginning of glacier retreat. The Cordillera Blanca is an example of this scenario.

Concha (1951) divided moraine-dammed lakes of the Cordillera Blanca into more categories. The first distinction is between moraine dams with steep slopes and moraine dams with gentle slopes, but no critical value is given, thus the

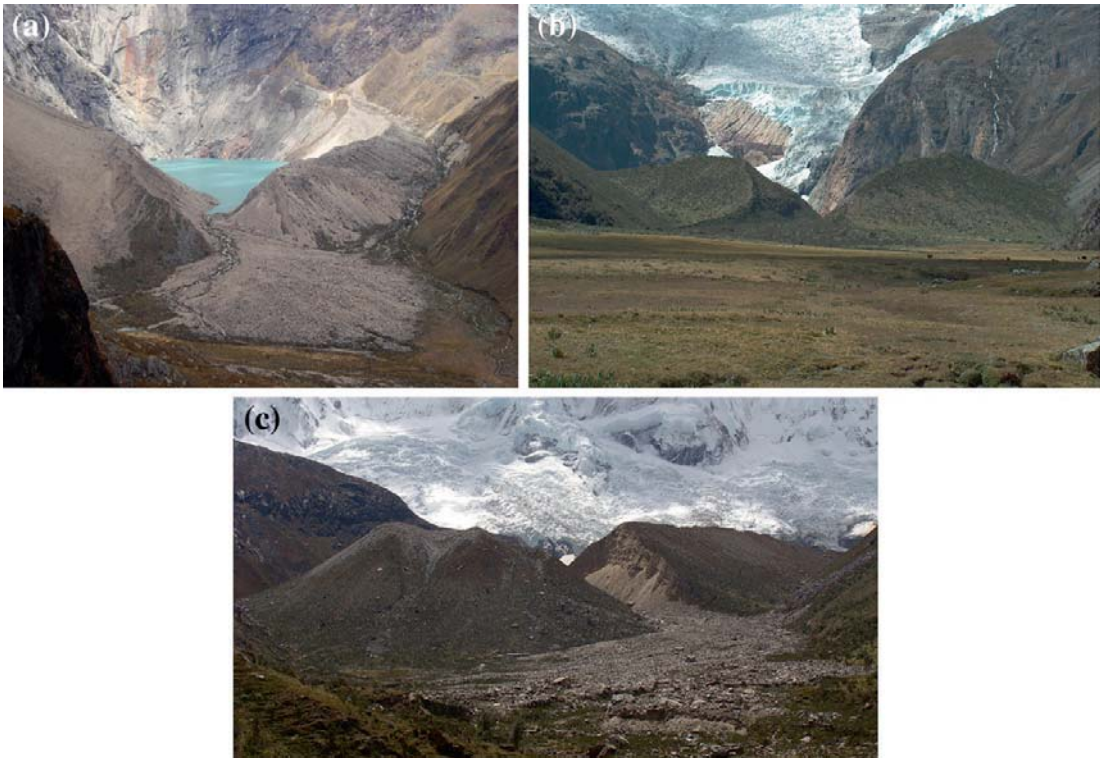

Fig. 3 Examples of failed moraine dams within the Cordillera Blanca. Part **a** shows the moraine dam of lake Jancarurish in de Los Cedros valley (failed in 1950), part **b** the moraine dam of lake Rajucolta in the Rajucolta valley (failed in 1883) and part **c** the moraine dam of lake Palcacocha in the Cojup valley (failed in 1941)

classification is quite subjective. The second distinction, in the case of bedrock-dammed lakes, is between moraine-dammed lakes with direct contact with glaciers and without direct contact with glaciers. These two characteristics in a simplified way reflect potential hazardousness of moraine-dammed lakes. That is, the slope of a moraine dam reflects its potential to failure and contact with glaciers reflects the possibility of icefall into the lake to trigger its failure.

Ice-dammed lakes are generally considered as one of the less stable types of lakes (Korup and Tweed 2007). Various subtypes of ice-dammed lakes were defined by Costa and Schuster (1988) according to the position of the lake in relation to the glacier. Only one subtype of ice-dammed lakes is represented in Cordillera Blanca—supraglacial lakes. This subtype of ice-dammed lakes is a product of surface glacier melting and evolves directly on the glacier tongue body. Merging of small lakes may produce a large one, but obvious instability of ice dams limit the possibility of development of supraglacial lakes of significant size. If glacier tongue is surrounded by moraines, merging of supraglacial lakes usually foregoes to formation of moraine-dammed lake.

There is no ice-dammed lake of significant size in the Cordillera Blanca at the moment, because these most frequently appear after damming of a lateral valley by an advancing glacier in the main valley, or after damming of the main valley by an advancing glacier from a lateral valley (Costa and Schuster 1988); but there is a high number of small supraglacial lakes that developed on glacier tongues with gentle slopes. Maximal perimeter of these lakes is in the order of tens of meters and the estimated volume of accumulated water reaches 10^4 m^3. Example of a site with a large number of ice-dammed lakes (subtype supraglacial lakes) is the tongue of Kogan glacier (Fig. 4a), beneath the northern slopes of Quitaraju massif (6,036 m a.s.l.). Development of these lakes indicates intense thinning of the Kogan glacier. The glacier tongue is not surrounded by a terminal moraine and thus the formation of a moraine-dammed lake by merging of small supraglacial lakes is not a possible scenario, in contrast to the tongue of Schneider glacier (Fig. 4b) beneath the eastern slopes of Huascarán Sur massif (6,768 m a.s.l.). The debris-covered tongue of Schneider glacier is surrounded by moraines, so there is a potential for future development of a significant moraine-dammed lake by merging of small supraglacial lakes.

3 Case Studies

Three examples illustrate the interconnections between glacier retreat, dynamic slope movements and potential hazards posed by developing glacial lakes. These events occurred in the last decade and caused material damages in affected valleys.

3.1 Lake Palcacocha 2003 Event

Lake Palcacocha is situated at the upper part of Cojup valley, which is oriented in the NE-SW direction under the Nevado Palcaraju (6,274 m a.s.l.) and Nevado Pucaranra (6,165 m a.s.l.). Terminal and lateral moraines were formed during the little ice age glacier advance, and with glacier retreat after this period a moraine-dammed lake formed and continued to expand. On 13rd December 1941, the moraine dam failed, probably after an icefall into the lake which produced a displacement wave, and the wave eroded the outflow of the dam (Oppenheim 1946). The volume of water released was estimated to be between 8×10^6 m^3 (Evans and Clague 1994) to 10^7 m^3 (Vilímek et al. 2005). The resultant glacial lake outburst flood transformed into debris flow, travelled down the valley, and invaded the city of Huaráz, where it claimed about 6,000 lives and destroyed one third of the whole city (Lliboutry et al. 1977). Currently, Lake Palcacocha is dammed by a basal moraine with two artificial dams (Fig. 5a) and its volume reached $17{,}325 \times 10^6$ m^3 during the 20th Century due to continuing glacier retreat (Vilímek et al. 2005).

A small GLOF was produced from Palcacocha Lake during March 19th 2003 by a planar landslide which crashed into the lake. The probable triggering factor was the over-saturation of the moraine material by precipitation. The 2003 landslide occurred in the inner part of the left lateral moraine adjacent to the glacial

Fig. 4 Tongues of Kogan glacier in 2012 (part **a**) and Schneider glacier in 2003 (part **b**) with tens of small supra-glacial lakes. The debris-covered tongue of Schneider glacier is surrounded by moraines and thus there is a potential for future formation and development of a moraine-dammed lake (*Source* Google Earth Digital Globe 2013)

tongue—in the location where prominent drop-offs of the moraine slope were identified on the 1970 aerial pictures (Vilímek et al. 2005). These features were also seen during fieldwork in 2003 (Zapata et al. 2003), and we assume that these might have played an important role in water infiltration and in the evolution of the planar sliding plane of the landslide. The landslide hits partly the glacial tongue. The volume of the slope movement was estimated to be about 50,000–75,000 m^3. A displacement wave which was created in the lake was at least 8 m high. The wave reached the frontal dam of Palcacocha Lake and after overtopping, it created a small GLOF in Cojup stream and Quilcay River. Fortunately large damages were avoided, nevertheless the water treatment plant for Huarás, capital city of Ancash

Fig. 5 View on lake Palcacocha with two artificial dams (*highlighted by the orange line*); steep nearly vertical lateral moraines are visible on both sides surrounding the lake. The detail picture (Part **b**) was taken after the 2003 event and captures the damaged artificial dam

department, was blocked by sediment-laden currents and also an aritificial dam of the lake was partly damaged (Fig. 5b). The landslide left no significant accumulation on the lakeshore. A secondary debris flow originated from the highly saturated material from the upper part of the moraine slope and produced a small accumulation cone. Field mapping around the glacial lake showed that the right lateral moraine on the opposite side of the lake shows signs of rather fresh but smaller planar landslides.

The most active parts of the entire inner slopes are those adjacent to the glacial tongue.The adjacent slopes became distabilized as the glacier retreated (Vilímek et al. 2005). This condition finally led to the landslides. Slopes without glacial support are turning towards a more stable profile based on the mechanical properties of the moraine material. This led to a gradual decrease in the inner moraine slopes and to the accumulation of moraine material in the lake. Evans and Clague (1994) mentioned with respect to high mountain slopes that the slope instability could persist after glacier retreat for perhaps hundreds of years. Comparison of remotely sensed data showed that the main phase of the glacial tongue retreat did not happend since 1970 (Vilímek et al. 2005). As a result of these processes, the maximal width of the lake is in the part adjacent to the glacial tongue.

The precise role of landslides in glacial retreat is not clear, but field investigations in 2004, after the March 2003 landslide, proved that part of the glacial tongue was destroyed and broken to small ice blocks by the landslide. The impact of these landslides might have contributed to glacier's disintegration in the past and therefore to its more rapid thawing. Our recent research in this area is focused on calculation of slope stability in moraines and on geophysical profiling, because other moraine blocks are distinguishably separated into left lateral moraine. The precise detachment zones have to be fixed to calculate their volumes.

3.2 Lake No. 513 2010 Event

The Lake No. 513 is a bedrock-dammed lake which is the largest of a group of three lakes situated in the central part of the Cordillera Blanca beneath the western slopes under Mt. Hualcán (6,122 m a.s.l.) with a water level of 4,437 m a.s.l. These slopes are formed by steep rock-walls fully covered by glaciers. This area consists of intrusive rocks formed from sharp modelled peaks and crests. Lithologically, they are composed of coarse-grained granodiorites and tonalites. Several hanging ice blocks were identified during our field inspection (2010 and 2011) as well as from satellite images. Ice and rock falls originating from similar settings represents devastating disasters in the Cordillera Blanca many times in the past (e.g. Zapata 2002; Klimeš et al. 2009). Frontal parts of the glaciers in the lake surrounding terminate in the altitude between 4,600 and 4,800 m a.s.l. depending on local morphology. However, the longest tongue reached the lake with an ice-fall crossing a 150 m high rocky step. Lake No. 513 is classified as a bedrock-dammed lake, before the artificial lowering of the water level, a combined bedrock and moraine dam was formed here after the glacier retreat. Now the moraine crest does not hold any water, which is entirely contained behind solid rocks.

During the 1970 earthquake in Ancash Peru, an ice avalanche from the eastern wall of the Hualcán mountain crashed into Lake Librón in the Huichajanca valley, in the Marañón River basin (Zapata 2002). Another event from Lake No. 513 happened in 1991 and was described by Carey et al. (2012). In April 11th 2010 a large block of glacier together with rocks, crashed from the southwestern part of Mt. Hualcán slope (Fig. 6a) into Lake No. 513 and part of the lake water overflowed the dam and created a GLOF in the Chucchún River valley, a right tributary to the Santa River. During this event some houses, roads, bridges and an important water treatment facility were destroyed, fortunately no fatality was recorded. The rather low extent of damage is due to the fact that the valley is not densely populated and some villages were out of reach of the debris flow. The debris flow went into the city of Carhuaz as well, but again only limited damages occurred. However, from geomorphologic point of view, this event was rather strong, because a large amount of material was transported down the valley. Lateral erosion was documented inside the valley (Fig. 6b) as well as large blocks accumulated at several places in the valley where stream power decreased (Fig. 6c). However, for the case of larger rock- or ice-fall into the lake, a much more serious disaster is likely to occur within the area in the near future.

Fig. 6 Part **a** shows Hualcán massif above Lake No. 513; the source area of 2010 ice and rock avalanche is *highlighted* by *orange circle*. Part **b** shows a part of Chucchún valley with dominance of erosional processes and part **c** shows a part of valley with dominance of accumulation processes

3.3 Lakes Artizon Alto and Artizon Bajo 2012 Event

Lakes Artizon Alto and Artizon Bajo are situated in a head of Artizon valley, which is a left-sided tributary of the Santa Cruz valley in northern part of the Cordillera Blanca. This is a part of the Rio Santa basin which drains into the Pacific Ocean. The Artizon valley is oriented to the North and is surrounded by three conspicuous peaks—Nevado Artesonraju (6,035 m a.s.l.) from the south-west, Nevado Parón (5,600 m a.s.l.) from the South, and Nevado Millisraju (5,500 m a.s.l.) from the East. The event which occurred on 8th February 2012 is one of the most recent GLOF events in the Cordillera Blanca, and it affected four lakes and two valleys. The sequence of important events in the formation and development of the Artizon lakes is reinterpreted below:

1. Glacier retreat was followed by formation and development (deepening) of the Artizon lakes; moraine-dammed lake Artizon Bajo is about 300 m long and 140 m wide with volume of accumulated water, 333,000 m^3 (Huaman 2001);

bedrock dammed Lake Artizon Alto is about 750 m long and 200 m wide, with a significant rock peninsula which divides the lake into two sub-basins (Fig. 7a)

2. Continuing retreat and thinning of the glacier tongue above the Lake Artizon Alto to the altitude of about 4,800 m a.s.l.
3. Steep lateral moraines are no longer supported by the glacier body and thus they are predisposed to slope movements; in 2001 it was recommended to lower the water level of Lake Artizon Bajo due to the possibility of landslides into Lake Artizon Alto (Huaman 2001)
4. On 8th February 2012, a landslide of the left lateral moraine (approximate volume in order of 3–8 × 10^5 m^3) into Lake Artizon Alto occurred (Fig. 7b), generating a displacement wave

   - the direct trigger of the landslide is not exactly known, but a probable trigger is precipitation (according to SENAHMI precipitation measurements in Yungay and Pamabamba, both about 25 km far from Arteson valley), there was intense precipitation during the last few days before this event)
   - another common trigger of dynamic slope movements in the Cordillera Blanca is earthquake, but according to the USGS earthquake archive, there was no earthquake on 8th February 2012 in the northern part of the Cordillera Blanca
   - we suggest that a moraine landslide may have occurred due to precipitation in combination with degradation caused by ice core melting.

5. The displacement wave following the landslide entered into the lake and overflowed the bedrock dam of Lake Artizon Alto and reached Lake Artizon Bajo.
6. The moraine dam of Lake Artizon Bajo was overflowed and a “positive feedback” effect caused a breach and moraine dam failure; the flood wave from Lake Artizon Alto increased its overall volume of about 2 × 10^5 m^3 water from Lake Artizon Bajo.
7. Escaped water transported a large amount of moraine material and significantly affected the Artizon valley (erosion in the upper part of the valley and deposition in the form of an alluvial fan in the mouth of the valley into the Santa Cruz valley. The central part of the Santa Cruz valley was also affected, mostly by accumulation processes, sand bar formation, and partial transfer of stream channel (Fig. 7c).
8. The released volume of water reached and then was partly absorbed by landslide-dammed lake Jatuncocha in the Santa Cruz valley; also material influx into the lake was significant, the lake was shortened by about 80 m and the lake area also decreased.
9. There was also minor damage to the artificial dam of Lake Jatuncocha due to increased flow rate.

Fig. 7 Lakes Artizon Alto and Artizon Bajo in 2003 before (part **a**) and in 2012 after (part **b**) the 2012 GLOF event. The *orange highlighted line* represents the extent of the glacier. Please note the significant glacier retreat. The *yellow color* in part **b** represents the accumulation of landslide of a lateral moraine, which entered the lake Artizon Alto on 8th February 2012. Part **c** demonstrates the dominant processes in the valleys Artizon and Santa Cruz after water release (*red color*—parts of the valley with erosion processes dominant; *green color*—parts of the valley with accumulation processes dominant) (*Source* Google Earth Digital Globe 2013)

10. Increased flow rate from Lake Jatuncocha with no sediment load eroded part of Santa Cruz valley before reaching another landslide-dammed lake (Lake Ichiccocha).
11. The rest of the flood wave was absorbed by Lake Ichiccocha.

In the affected valleys (the Artizon and Santa Cruz), we may generally distinguish between areas where erosion processes are prevalent and areas where accumulation processes are prevalent. Erosion processes are prevalent on the steeper parts of the valley, while accumulation processes are prevalent on the flatter parts (Fig. 7c), except for a short flat part of the Santa Cruz valley beneath the Lake Jatuncocha which was eroded by increased flow rate from this lake, because all transported material was retained in the Jatuncocha Lake basin. The stream banks in the steeper upper part of Artizon valley are more prone to slope movements after the incision of the stream channel (undercutting the slopes), thus there is a possibility of future slope movements and formation of a landslide-dammed lake. An alluvial fan that was originally 300 m wide on the flatter part of the Artizon valley has been extended to 500 m wide by transported material. The position of the stream channel in the Santa Cruz valley has been changed by the accumulation of sediment bars. This example shows how a local landslide into the lake may subsequently affect valleys and lakes, which are kilometers away.

4 GLOFs: A Manageable Hazard??

The region of the Cordillera Blanca is relatively densely populated, so there is urgent need to manage various natural hazards including GLOFs following sudden release of water from any type of glacial lake. As shown above, occurence of GLOF is a highly complex question which is strongly linked with other types of natural hazards, mainly with dynamic slope movements or large earthquakes. These hazards are difficult to quantify or to predict precisely in time, thus it is not possible to completely prevent hazards associated with sudden release of water from glacial lakes. Richardson and Reynolds (2000a) listed three phases of glacial hazard management: the first phase is identification of a potential hazard, followed by hazard assessment (second phase), and ideally, the third phase is hazard mitigation. Thanks to ongoing formation and development of all types of glacial lakes in the Cordillera Blanca, it is important to reassess their potential hazards thoroughly. Potential hazard identification and reliable assessment are crucial steps in risk estimation and effective management (Fig. 8).

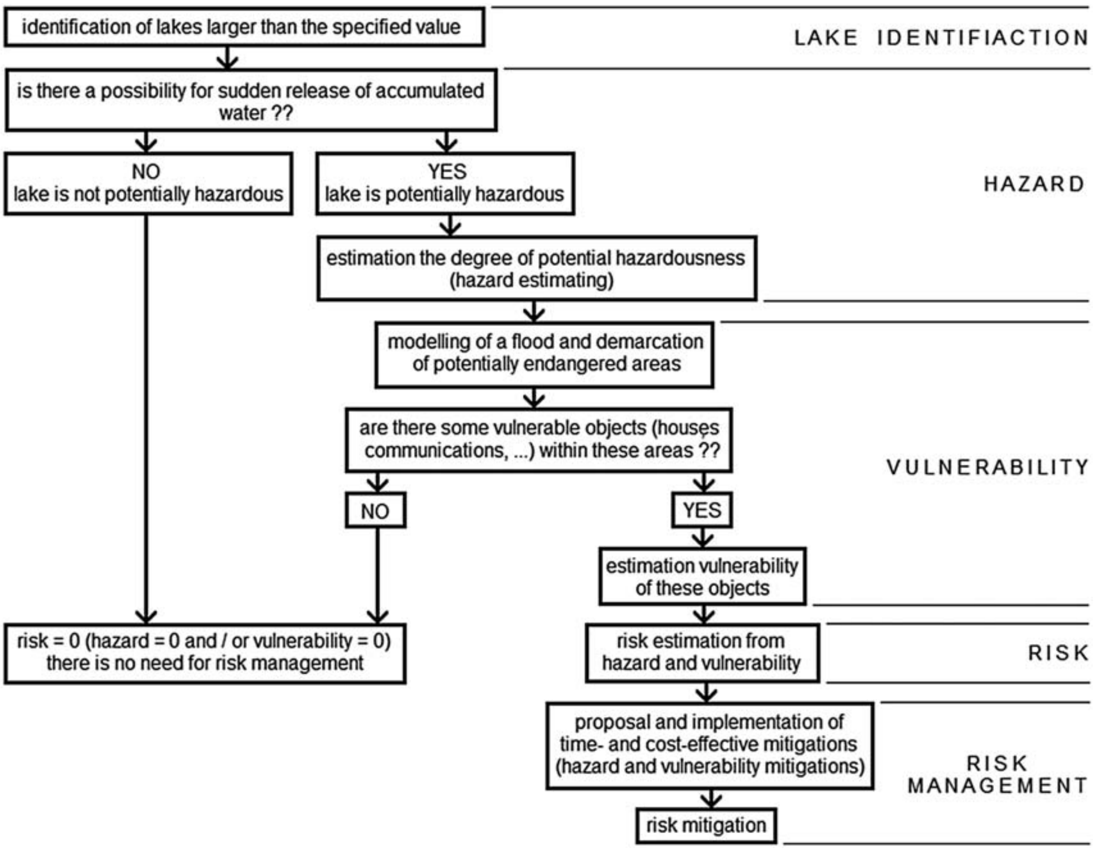

Fig. 8 Schematic procedure for GLOF risk management [According to: Huggel et al. (2004); Hegglin and Huggel (2008); Richardson (2010), and Shrestha (2010)]

4.1 Hazard Assessment

New potentially dangerous lakes are forming and developing (Klimeš 2012), and existing lakes are rapidly changing their characteristics. It is highly important to realize that potential hazardousness of glacial lakes is changing significantly during short time periods, because high mountain environment is one of the most dynamic natural environments worldwide. The previous examples of Lake Palcacocha and Lake No. 513 showed that GLOFs may occur even from a lake on whose dam has been remediated, and which was considered as safe. Lake Palcacocha changed from a "safe lake" to one producing a GLOF in 30 years between the 1970′s and 2003 (Vilímek et al. 2005). During this period, the glacier retreated about 1,000 m. This intense deglaciation led to rapid increase of water volume accumulated in the lake. Also, lateral moraines with steep slopes were uncovered and thus ready for landslide into the lake (2003 event). These are remarkable changes, and also the reason why the results of hazard assessment should be reevaluated after a certain period of time.

There are two phases of GLOF hazard assessment. The first phase aims at estimating the possibility of sudden water release from any given glacial lake, while the second phase aims at modelling the flood wave downstream, determining the endangered areas, estimating the probability of debris-flow occurrence and the probable maximal travel distance (Huggel et al. 2004). There are a number of methods for GLOF hazard assessment, but these events in Cordillera Blanca differ in some ways from other world regions. These differences consist in share and representation of causes of sudden water release and also in high number of remedial work applied on dams in the Cordillera Blanca (see Sect. 4.2 Hazard mitigation). This is necessary to be accounted for in precise hazard assessment for glacial lakes within the Cordillera Blanca (Emmer and Vilímek, 2013).

4.2 Hazard Mitigation

Lakes of the Cordillera Blanca are famous for the high number of remedial projects (Carey 2005), which have been implemented since the 1940s. There are about forty glacial lakes with dams that have been remediated (Reynolds 2003). Three different types of remedial works were most commonly applied on glacial lakes within this region:

1. Open cut—Open cut is carried out by countersinking the outlet of lakes which do not have a solid rock dam (moraine-dammed lakes). The countersunken outlet is usually combined with artificial dam construction, but sometimes is not (e.g. Lake Arhueycocha). Open cut cannot be applied to bedrock-dammed lakes, therefore in this case tunnels are used (see below) to lower the water level permanently. Open cut allows the water level to be decreased and thus reduces the volume of accumulated water.
2. Artificial dam—The main purpose of an artificial dam is to increase dam freeboard and thus enable the dam to be resistant against displacement waves generated by dynamic slope movements into the lake. Most significant glacial lakes within the Cordillera Blanca were remediated by a combination of a concrete outflow and an artificial dam [e.g. Lake Llaca (Fig. 9a), or Lake Rajucolta (Fig. 9b)]
3. Tunnel—Tunnels are used to decrease and limit the water level of bedrock-dammed lakes (e.g. Lake No. 513; Fig. 9c), or of moraine-dammed lakes with a naturally high freeboard but without a natural surface outflow (e.g. Lake Safuna Alta).
4. Siphon—Siphons are used to lower the water level before remedial work is done (usually before open cut countersink or tunnel excavation is carried out), however this is not a permanent solution. Figure 9d shows siphons installed in 2011 to lower the water level of Lake Palcacocha.

As shown above, sudden water release from Lake Palcacocha and Lake No. 513 occured despite the fact that they had been remediated. These lakes were chosen to be remediated, because they were adjudged to be potentially hazardous, and thus remedial work was done. If remedial work had not been done, the volume of released water would have been much larger and thus the impacts would have been

Fig. 9 Examples of remedial works. Part **a** shows artificial dam and concrete outlet of lake Llaca in the central part of the Cordillera Blanca; dam freeboard is 12 m. Part **b** captures ongoing work on the dam of lake Rajucolta in 2004. Part **c** shows the entrance to the tunnel excavated in the bedrock dam of lake No. 513 (*red arrow*). Part **d** shows six siphons installed in fall 2011 to drain and lower the water level of lake Palcacocha

more catastrophic. Water released from lakes of remediated dams should not be interpreted as failure of the remedial works, but as improvement in hazard assessment, because it is not entirely possible to prevent GLOFs only by remedial work on the lake dam. Also, vulnerability mitigation such as urban planning based on demarcation of potentially endangered areas should be done to eliminate fatalities and significant material damages.

5 Conclusions

The number of potentially hazardous lakes within the Cordilllera Blanca is increasing due to the ongoing glacier retreat and parallel glacial lake formation and development in this heavily glacierized tropical range of the world. Furthermore, the number of lakes is currently estimated to be more than one thousand within this region and this number is still increasing. There are three types of glacial lakes within the Cordillera Blanca which evolve with glacier retreat in altitudes between

4,600 m a.s.l. and 5,000 m a.s.l. These are: (1) bedrock-dammed lakes; (2) moraine-dammed lakes; and (3) ice-dammed lakes. Significant lakes, having volumes exceeding 10^6 m^3 of accumulated water, are of the first and second type, while ice-dammed lakes do not reach this volume in the Cordillera Blanca. All types of glacial lakes may produce glacial lake outburst floods, nevertheless lakes dammed by Little Ice Age moraines are generally supposed to be potentially the most hazardous in these days, because they are dammed by unstable moraines and are frequently close to the present glaciers and the volume of accumulated water is often great. Floods from any type of glacial lake are most commonly caused by dynamic slope movements into the lake, producing displacement waves, which breach or overflow the lake dam. The slope movements can be either direct or indirect, and are associated with deglaciation. Dynamic slope movements are mostly icefalls from hanging or calving glaciers or landslides of newly exposed lateral moraines. These events claimed thousands of lives and caused significant material damage within the Cordillera Blanca since the end of the Little Ice Age. Presented examples of Lake Palcacocha, Lake No. 513 and Lakes Artizon Alto and Artizon Bajo showed that the threat of GLOF is real and will require appropriate and continued attention well into the 21st Century when glacier retreat continues and even accelerates.

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