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Hazard mitigation of glacial lake outburst floods in the Cordillera Blanca (Peru): the effectiveness of remedial works

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Abstract

Almost 40 glacial lakes have been remediated in the Cordillera Blanca since the 1940s by implementing different types of structural measures to prevent (mitigate) glacial lake outburst floods. These are (1) open cuts; (2) artificial dams; (3) tunnels; and their combinations. The first part of the paper provides an overview and description of the implemented remedial works. In the second part, the effectiveness of these remedial works is evaluated on the basis of a comparison of the quantified susceptibility of nine selected lakes to outburst floods before and after remediation. Our investigation showed that different types of remedial works have different impacts on the susceptibility of a given lake to outburst floods and are effective for different scenarios (causes and subsequent mechanisms) of outburst floods. Hazard management implications in the framework of risk management and ongoing geo-environmental change are also discussed.

Introduction

'Glacial lake outburst flood' (GLOF) is a term used to describe a flood following a sudden and often catastrophic release of water retained in a glacial lake, irrespective of the cause (e.g. Richardson and Reynods, 2000). This phenomenon is especially frequent in high mountain areas, which are currently being deglaciated (Clague *et al*., 2012). Tens of GLOFs have occurred in the Cordillera Blanca (e.g. Ames, 1985; Zapata, 2002), the highest mountain range in Peru, since the end of the last significant glacier advance – the Little Ice Age – culminating here in the 19th century (Thompson *et al*., 2000; Solomina *et al*., 2007). Some of these events claimed hundreds of lives and caused significant material damage (Lliboutry *et al*., 1977; Zapata, 2002; Emmer *et al*., 2014).

Mitigation of GLOFs within the Cordillera Blanca has a long history. The first attempts to prevent these events by implementation of structural measures in the lakes (so-called 'lake security projects'; Carey, 2005) were made in the 1940s (Broggi, 1942; Concha, 1952). This was in response to a catastrophic GLOF following dam failure on Lake Palcacocha and the downstream-situated Lake Jircacocha in 1941, which claimed around 6000 lives in the city of Huaráz (Oppenheim, 1946; Lliboutry *et al*., 1977). From this point of view, the Cordillera Blanca is one of the pioneering regions, and the overall number of remediated lakes is extraordinary. Nonetheless, it is clear that GLOF risk management poses a great scientific and engineering challenge to the sustainable development of high mountain areas worldwide (e.g. Richardson, 2010; Schaub *et al*., 2013; Vilímek *et al*., 2014). In accordance, glacial lakes have also been remediated in the Alps (Lichtenhahn, 1971, 1979; Röthlisberger, 1971; Haeberli *et al*., 2001), Scandinavia (Grabs and Hanisch, 1993), and especially in the Hindu Kush–Himalaya region (e.g. Ives, 1986; Reynolds, 1999; Rana *et al*., 2000; Kattelmann, 2003; Richardson, 2010; Shrestha, 2010).

The aim of this work is to provide a brief overview of the remedial works implemented in the glacial lakes of the Cordillera Blanca, to evaluate the effectiveness of these measures, and to discuss the applicability. Evaluating the effectiveness of different types of remedial works is based on an assessment of pre- and post-remediation susceptibility of nine selected glacial lakes to outburst floods.

Methods and data

Methods

The first part of this paper (section *Remedial works and their application: an overview*) provides an overview of the different types of remedial works implemented in the glacial lakes of the Cordillera Blanca to prevent or mitigate the catastrophic impacts of GLOFs. The pre- and post-remediation condition (susceptibility to outburst floods) of nine selected glacial lakes (see Figure 1) is assessed to evaluate the effectiveness of these works (section *Results*). The method presented by Emmer and Vilímek (2014) for a first-order assessment of the susceptibility of glacial lakes to outburst floods verified on lakes within the studied region of the Cordillera Blanca was used for this purpose.

This method takes into consideration the implementation of different types of remedial works and regional specifics of the causes and mechanisms of GLOFs in the Cordillera Blanca (Emmer and Vilímek, 2013). The method uses 17 characteristics largely obtainable from remotely sensed data and is based on a combination of decision trees and numerical calculations, providing five separate results for five different GLOF scenarios previously recorded in the studied region (see Table 1). Naturally, some of these scenarios are inter-related (Scenarios 1 and 3; Scenarios 2 and 4). Each scenario is a product of two or three components (see Table 1), depending on the procedure for the given scenario (for more detailed description, see Emmer and Vilímek, 2014). The result of each component is a figure between 0 and 1, and therefore, the result of each scenario is also a figure between 0 and 1, where 1 is the maximum susceptibility for outburst floods in the given scenario. If a scenario is not possible for a given lake (e.g. dam failure of bedrock-dammed lake), 'Not Applicable' is used.

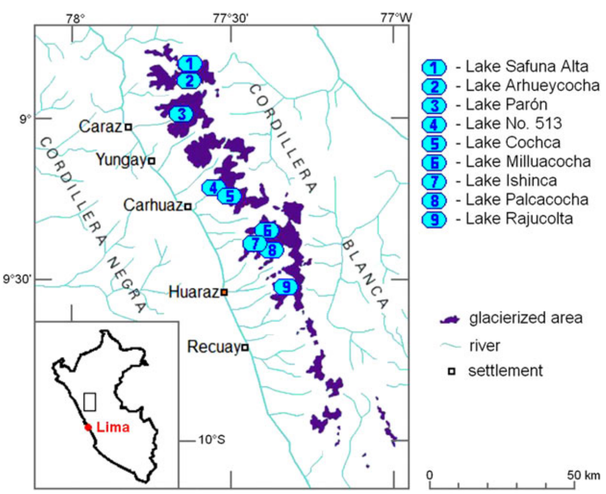

Figure 1 Location of the studied lakes (base map modified from USGS maps).

Input data

The basic characteristics of nine studied lakes are listed in Table 2. These lakes were chosen because (1) different types of remedial works have been implemented; (2) different types of lakes are represented; and (3) historical data (especially for their pre-remediation condition) were available. Input data for the susceptibility assessment were obtained from (1) field surveys carried out in May/June 2012, June/July 2013 and May/June 2014 at a majority of the studied localities (geomorphological mapping, detailed topographical measurements using laser inclinometer and rangemeter with a resolution of 1°/0.01 m); (2) unpublished research reports from the archive of Autoridad Nacional del Agua (ANA; Huaráz, Peru); (3) historical aerial photos for the periods 1948–1950, 1962, and 1970; (4) high-resolution satellite images (USGS, NASA, SPOT, CNES, ASTRIUM) available on Google Earth Digital Globe 2014, covering the study area since 1970; and (5) topographical maps from the Peruvian cadastral office at a scale of 1:25 000, with basic contour intervals of 25 m. A comprehensive list of input data used for assessing the pre- and post-remediation susceptibility of the nine studied lakes is included in Table A1.

Remedial works and their application: an overview

History of remedial works and decision-making criteria

Induced by the 1941 catastrophe damaging the city of Huaráz (see Introduction), the Peruvian government decided to pay more attention to the glaciers and lakes of the Cordillera Blanca, resulting in the establishment of the expert commission. Based on the expert recommendation of the commission members (including foreign experts H. Kinzl and B. Schneider), four lakes (Shallap, Tullparaju, Mullaca, and Jancarurish) were chosen for remediation by performing an open cut through the moraine dam in this initial phase.

The Comisión de Control de Lagunas de la Cordillera Blanca (CCLCB) was established in 1950. Based on an expert analysis of the set of aerial photos taken between 1948 and 1950, the first inventory of the lakes within the Cordillera Blanca was made, mentioning 230 lakes of 'significant size', and hazardous lakes were detected. The assessment criteria were (1) direct contact with the glacier (yes or no); (2) dam type (moraine or bedrock); and (3) steepness of the dam (in the case of moraine-dammed lakes). Moraine-dammed lakes in direct contact with the

Table 1 Scenarios and their components used in the method for assessing the susceptibility of glacial lakes to outburst floods (based on Emmer and Vilímek, 2014)

Scenarios	Description of the scenario	Components
Scenario 1	Dam overtopping resulting from a fast slope movement into the lake	Potential for fast slope movement into the lake Potential for dam overtopping by displacement wave
Scenario 2	Dam overtopping following a flood wave originating in a lake situated upstream	Potential for flood wave from a lake situated upstream Retention potential of assessed lake
Scenario 3	Dam failure resulting from a fast slope movement into the lake	Potential for fast slope movement into the lake Potential for dam overtopping by displacement wave Dam erodibility for Scenario 3
Scenario 4	Dam failure following a flood wave originating in a lake situated upstream	Potential for flood wave from a lake situated upstream Retention potential of assessed lake Dam erodibility for Scenario 4
Scenario 5	Dam failure following a strong earthquake	Potential for strong earthquake Dam instability

Susceptibility to outburst flood for a given scenario is calculated as a product of involved components.

Table 2 Studied lakes and their basic characteristics (modified according to Reynolds, 2003; Cochachin *et al*., 2010; Cochachin and Torres, 2011)

Lake	Valley	Co-ordinates	Lake level altitude (m a.s.l.)	Dam type	Lake volume ($\times$ 1000 m^3) (year)	Type of implemented remedial works (year)
Arhueycocha	Santa Cruz	8°53′15″ S 77°37′45″ W	4400	Moraine	19 551 (2011)	Open cut (2000); lake level lowering 8 m
Cochca	Hualcán	9°13′00″ S 77°32′40″ W	4538	Moraine/ bedrock	1001 (2011)	Open cut (1953); lake level lowering 3 m
Ishinca	Ishinca	9°23′25″ S 77°24′55″ W	4960	Moraine	786 (2004)	Open cut + artificial dam (1951); lake level lowering 6 m
Lake No.513	Hualcán	9°12′45″ S 77°33′00″ W	4431	Bedrock	9251 (2010)	Tunnel (1994); lake level lowering 20 m
Milluacocha	Ishinca	9°21′45″ S 77°24′40″ W	4577	Moraine (failed in 1952)	3985 (2011)	Open cut (2000); lake level lowering 6 m
Palcacocha	Cojup	9°23′40″ S 77°22′40″ W	4566	Moraine (failed in 1941)	17 325 (2009)	Open cut + artificial dam (1974); lake level lowering 3 m
Parón	Parón	8°59′45″ S 77°40′30″ W	4152–4182*	Moraine/ rock glacier	14 275–26 976* (2007)	Tunnel (1984); lake level lowering regulable up to 52 m
Rajucolta	Rajucolta	9°31′30″ S 77°20′40″ W	4273	Moraine	17 546 (2004)	Open cut + artificial dam (2004); lake level lowering 10 m
Safuna Alta	Collota	8°50′30″ S 77°37′10″ W	4360	Moraine	15 524 (2010)	Tunnel (1970; 1973) lake level lowering 0 m

*Depends on regulable water level.

glacier and with steep slopes of the dam were assessed as the most hazardous lake type (Concha, 1952). In addition, lake volume and the location of settled areas downstream were considered.

In the second half of the 20th century, the number of remediated lakes increased. The specific type of remediation for a given lake was selected based on detailed geological, geomorphological, glaciological, and geophysical surveys. Additional fundamental criteria were technological and economical feasibility. For these reasons, only five lakes are equipped with tunnels, even though this is considered the most appropriate remedial technique (see also Grabs and Hanisch, 1993). A recent knowledge exchange with foreign experts (from e.g. Switzerland, United Kingdom) also helped with hazard assessment and mitigation.

Types of remedial works implemented in the Cordillera Blanca

Different types of remedial works aiming to reduce the threat of GLOFs have been implemented to the dams of glacial lakes worldwide (Grabs and Hanisch, 1993), and there are three main types of permanent remedial works in the glacial lakes of the Cordillera Blanca since the 1940s (Oppenheim, 1946; Concha, 1952; Portocarrero, 1984; Carey, 2005). These are (1) open cuts; (2) artificial dams; (3) tunnels, and their combination. Almost 40 glacial lakes and several landslide-dammed lakes have been remediated. A comprehensive list of remediated lakes has been presented by Zapata (1978) and later by Reynolds (2003). Hand in hand with the rapid evolution of the selected lakes, remedial works are continuing to date (e.g. lowering of the level of Lake Palcacocha in the Cojup Valley using six siphons; Emmer *et al.*, 2014).

Open cuts are implemented by cutting through the moraine dam to lower and/or fix the lake level (and thereby the volume of retained water). Another goal is to prevent a surface outlet due to erosion following a sudden increase in flow rate (e.g. after an icefall into the lake) by cementation and concreting. Open cuts are mostly combined with artificial dams in the Cordillera Blanca (see below), but there are cases where they are implemented independently (e.g. Lake Arhueycocha in the right tributary of the Santa Cruz Valley, Lake Cochca above Lake No. 513 in the Hualcán Valley, or Lake Milluacocha in the Ishinca Valley; see Figure 2(a)).

Artificial dams (Figure 2(b)) are built especially to increase dam freeboard (and thereby the retention potential of the lake) and to prevent a lake outlet due to the direct impact of a displacement wave(s) and unexpected increase(s) in water levels. Artificial dams are usually built from concrete or stone walls with earthen fill, and they are often more than 10 m high. They are implemented solely in moraine-dammed lakes in the Cordillera Blanca and mostly in combination with open cuts (see above), above the lake outlet or in other locations where the dam freeboard needs to be increased (usually a naturally lowered point on the moraine crest; see Figure 2(c), (d)).

Tunnels are generally used to lower lake levels (increase dam freeboard) and/or to fix a lake at its current level. If they are equipped with a regulating device, then the lake level may be changed according to the actual requirements (e.g. tunnel installed in Lake Parón). It is important to realise that tunnel digging in remote high-mountain regions at an elevation of above 4500 m a.s.l. is technologically and financially demanding; thus, only five tunnels have been implemented in the glacial lakes of the Cordillera Blanca (see above). There are two types of tunnels implemented according to the drilled material: (1) tunnels dug through the moraine material and (2) tunnels dug through the bedrock.

There are two examples of lakes equipped with tunnels dug through the moraine dam in the Cordillera Blanca, Lake Safuna Alta in the Collota Valley and Lake Tullparaju in the Quilcaynuanca Valley. Tunnels dug through the moraine material are generally susceptible to damage during large earthquakes. An example is the 1970 catastrophic earthquake resulting in tunnel damage and subsequent piping at Lake Safuna Alta (Lliboutry *et al.*, 1977; Hubbard *et al.*, 2005). There are two subtypes of tunnels dug through the bedrock – tunnels dug through the bedrock dams of bedrock-dammed lakes (Lake No. 513 in the Hualcán Valley (Figure 3(a), (b); see also Reynolds *et al.*, 1998) and Lake Cullicocha in the tributary of the de los Cedros Valley) and tunnels dug through the bedrock surrounding a moraine-dammed lake (Lake Parón in the Parón Valley; Figure 3(c), (d)). These constructions are generally considered to be more resistant to earthquakes.

Results

Pre- and post-remediation susceptibility to outburst floods

The susceptibility of the nine selected glacial lakes to outburst floods before and after the implementation of remedial works is presented in Table 3. Before remediation, all of the studied lakes were most susceptible to outburst floods in Scenario 1 (dam overtopping resulting from a fast slope movement into the lake), with the exception of Lake Parón, which was most susceptible in Scenario 2 (dam overtopping following a flood wave originating in a lake situated upstream). Scenario 2 was the possible scenario for three other lakes (Milluacocha, Rajucolta and Lake No. 513). Scenario 3 (dam failure resulting from a fast slope movement into the lake) was assessed as being a possible scenario for all of the studied lakes, with the exception of Lake No. 513, which has a bedrock dam and is not susceptible to dam failure. Three lakes (Milluacocha, Rajucolta and Parón) were susceptible to outburst floods in Scenario 4 (dam failure following a flood wave originating in a lake situated upstream). Eight lakes were susceptible to outburst floods in Scenario 5 (dam failure following a strong earthquake).

After the implementation of remedial works, the number of lakes susceptible to outburst floods in Scenarios 1 and 5 remained the same, but the susceptibility was reduced in the majority of cases (see Table 3). The number of lakes susceptible to outburst floods in Scenario 2 decreased from

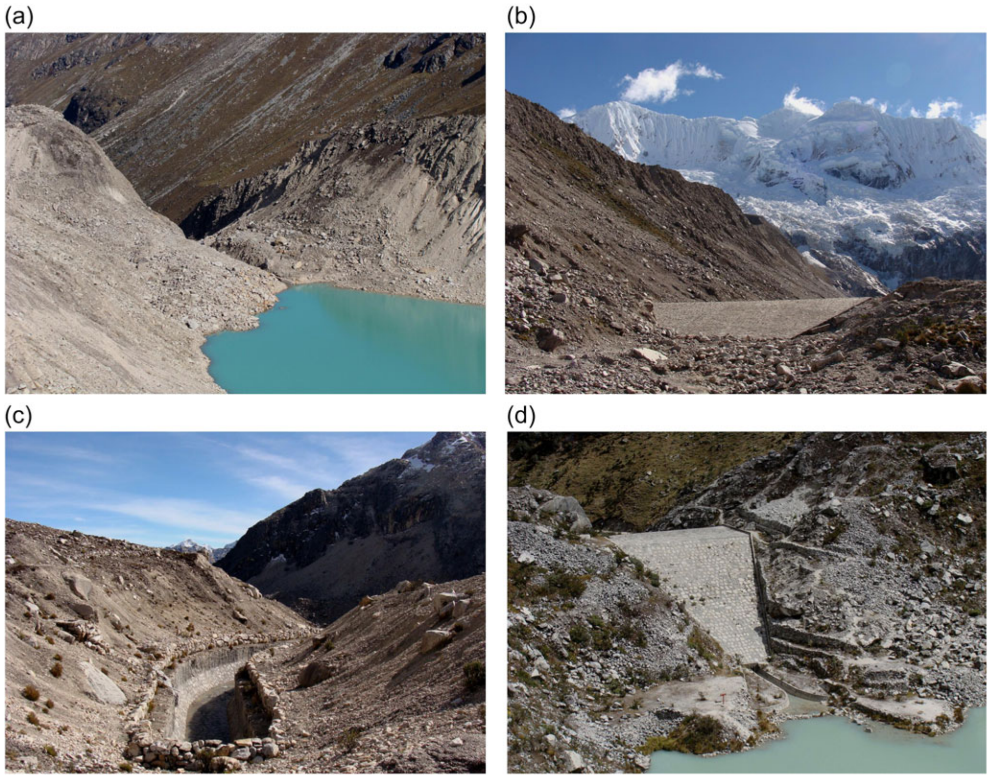

Figure 2 Example of open cuts and artificial dams. (a) A failed moraine dam of Lake Milluacocha equipped in 2000 with an open cut; (b) a separate artificial dam increasing the dam freeboard of Lake Palcacocha in the naturally lowered part of the dam crest (not the lake outflow); (c) a downstream view of the open cut of Lake Ishinca from an artificial dam providing a freeboard of 5 m; and part (d) an artificial dam providing a freeboard of 12 m and an inlet to the open cut draining Lake Llaca.

four to one, the number of lakes susceptible to outburst floods in Scenario 3 decreased from eight to two, and the number of lakes susceptible to outburst floods in Scenario 4 decreased from three to zero. The implementation of remedial works also changed the order of lakes from most to less susceptible. Lakes Ishinca, Palcacocha, and Lake No. 513 were the most susceptible to outburst floods before the remediation (all with a result of 1.000), while lakes Milluacocha (0.985), Ishinca, (0.952) and Palcacocha (0.913) were the most susceptible to outburst floods after the remediation.

Change in susceptibility to outburst floods in relation to the type of remedial works

The change in susceptibility between the pre-remediation and post-remediation condition of the nine studied lakes (see Table 3) in relation to the type of implemented remedial works indicates that:

1. the implementation of *open cuts* (lakes Arhueycocha, Cochca and Milluacocha):

- did not influence the susceptibility to outburst floods in Scenarios 1 and 2 (dam freeboard = 0 m);
- eliminates the susceptibility to outburst floods in Scenario 3 and 4 (component *dam erodibility* is considered to be 0 after the remediation; see Emmer and Vilímek, 2014); and
- slightly decreases the susceptibility to outburst flood in Scenario 5 (in the case of lake level lowering and changing dam geometry).

2. the implementation of a combination of *open cuts and artificial dams* (lakes Palcacocha, Rajucolta and Ishinca):

- slightly decreases the susceptibility to outburst floods in Scenario 1;
- eliminates the susceptibility to outburst floods in Scenarios 2 and 4, where relevant [in the case of Lake Rajucolta, retention capacity of the lake after the remediation (component *retention potential of assessed lake*) is higher than volume of any of upstream situated lakes; therefore, susceptibility to outburst flood in this scenario is eliminated to 0];
- eliminates the susceptibility to outburst floods in Scenario 3; and

Figure 3 Examples of lakes equipped with tunnels. (a) A bedrock dam of Lake No. 513 partly covered by moraine material, and the debris-free bedrock indicates the original water level before being lowered 20 m; (b) the outlet of a tunnel dug through the bedrock dam of Lake No. 513; (c) an overview of Lake Parón from the Jatunraju glacier damming the lake (note the light belt around the lake indicating a decrease in the water level of about 40 m); and (d) the outlet of the tunnel below Lake Parón.

- slightly decreases the susceptibility to outburst floods in Scenario 5.

3. the implementation of *tunnel(s) lowering the water level* (Lake Parón and Lake No. 513):

- significantly decreases the susceptibility to outburst floods in Scenario 1;
- eliminates the susceptibility to outburst floods in Scenarios 2 and 4;
- slightly decreases the susceptibility to outburst floods in Scenario 3, where relevant (the case of Lake Parón); and
- did not influence the susceptibility to outburst floods in Scenario 5, where relevant (in the case of Lake Parón, the dam geometry did not change; therefore, component *dam instability* did not change).

4. the implementation of *tunnel(s) conserving the original water level* (Lake Safuna Alta):

- did not influence the susceptibility to outburst floods in any of the defined scenarios (it is rather designed to prevent the blockage of outflow channels in the case of a lake without a surface outflow).

Discussion

Lake evolution over time

The susceptibility of a given lake to outburst floods is not constant and may change significantly over time, especially due to changes in the lake (dam) setting and the setting of the lake's surroundings (e.g. Iturrizaga, 2014; Emmer *et al.*, 2015). The susceptibility may decrease or increase over time. Factors contributing to a decrease in susceptibility are (1) glacier retreat and elimination of calving into the lake; (2) natural stabilisation of moraine slopes surrounding the lake; and (3) remedial works. Factors contributing to an increase in susceptibility are (1) glacier retreat followed by exposure of steep moraine slopes susceptible to landslides into the lake; (2) slope response to permafrost degradation in the lake's surroundings; (3) dam degradation (e.g. piping, slope movements on the dam body, buried ice melting); and (4) evolution of new hazardous lakes upstream.

There are several cases in the Cordillera Blanca, where such natural evolution has significantly changed the

Table 3 Pre- and post-remediation susceptibility of the studied lakes to outburst floods

Lake	Pre-remediation susceptibility for outburst flood in:					Post-remediation susceptibility for outburst flood in:				
	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Arhueycocha	0.866	Not applicable	0.459	Not applicable	0.142	0.866 (0.000)	Not applicable	0.000 (−0.459)	Not applicable	0.130 (−0.012)
Cochca	0.766	Not applicable	0.120	Not applicable	0.004	0.766 (0.000)	Not applicable	0.000 (−0.120)	Not applicable	0.001 (−0.003)
Milluacocha	0.985	0.819	0.255	0.212	0.058	0.985 (0.000)	0.819 (0.000)	0.000 (−0.255)	0.000 (−0.212)	0.055 (−0.003)
Ishinca	1.000	Not applicable	0.423	Not applicable	0.154	0.952 (−0.048)	Not applicable	0.000 (−0.423)	Not applicable	0.067 (−0.087)
Palcacocha	1.000	Not applicable	0.174	Not applicable	0.054	0.913 (−0.087)	Not applicable	0.000 (−0.174)	Not applicable	0.026 (−0.028)
Rajucolta	0.707	0.643	0.276	0.060	0.044	0.668 (−0.039)	0.000 (−0.643)	0.000 (−0.276)	0.000 (−0.060)	0.025 (−0.019)
Lake No. 513	1.000	0.766	Not applicable	Not applicable	Not applicable	0.876 (−0.124)	0.000 (−0.766)	Not applicable	Not applicable	Not applicable
Parón	0.643	0.906	0.199	0.235	0.036	0.505* (−0.138)	0.000* (−0.906)	0.156* (−0.043)	0.000* (−0.235)	0.036 (0.000)
Safuna Alta	0.604	Not applicable	0.279	Not applicable	0.231	0.604 (0.000)	Not applicable	0.279 (0.000)	Not applicable	0.231 (0.000)

The change in susceptibility is shown in brackets (a decrease in susceptibility is highlighted in red). Scenario 1: dam overtopping resulting from a fast slope movement into the lake; Scenario 2: dam overtopping following a flood wave originating in a lake situated upstream; Scenario 3: dam failure resulting from fast slope movement into the lake; Scenario 4: dam failure following a flood wave originating in a lake situated upstream; Scenario 5: dam failure following a strong earthquake.
*Calculated for the lowest possible water level.

susceptibility of lakes to outburst floods. An example is Lake Palcacocha in the Cojup Valley, where, because of the continuing glacier retreat and rapid lake growth over the last few decades, a decision was taken to rebuild the existing remedial works (open cut and two artificial dams providing 8 m of freeboard) and increase the dam freeboard. In addition, six siphons were installed in 2011 in order to lower the lake level (reduce the volume of retained water; A.Cochachin, ANA, personal communication).

GLOFs from previously remediated lakes

Remedial works are unable to completely eliminate the threat of GLOFs, but they can at least partly help to mitigate their catastrophic impacts. Several GLOFs from previously remediated lakes have been recorded in the Cordillera Blanca, which is evidence of the effective implementation to the most hazardous lakes (Emmer *et al.*, 2014). The best known cases are 2003 GLOF from Lake Safuna Alta (Hubbard *et al.*, 2005) and 2010 GLOF from Lake No. 513 (Carey *et al.*, 2012b; Klimeš *et al.*, 2014; Vilímek *et al.*, 2015). These events were caused by unexpected high-volume fast slope movements into the lake, and GLOFs occurred despite the tens of metres of freeboard. In the case of Lake Safuna Alta, the implemented remedial works had no impact on the event because the constructed tunnel only fixed the original water level, while tunnels lowering the lake level by 20 m significantly mitigated the 2010 GLOF in the case of Lake No. 513. Another example is the 2003 GLOF in Lake Palcacocha following a landslide of part of the left lateral moraine surrounding the lake, producing a displacement wave that overtopped the lake dam despite a freeboard of 8 m (Vilímek *et al.*, 2005).

Hazard mitigation of GLOFs in the framework of risk management

Faced with ongoing global change, manifesting itself in the form of the deglaciation of the majority of high mountain ranges and the related formation and evolution of glacial lakes, the need for reliable risk identification, assessment, and effective mitigation is apparent worldwide (e.g. Carey *et al.*, 2012a; Schaub *et al.*, 2013; Westoby *et al.*, 2014). Besides hazard mitigation, which is generally considered to be at a good level in the Cordillera Blanca, the second fundamental component in risk management is vulnerability mitigation, which is definitely not optimal at some localities. Houses of poor people are often poorly constructed and are often built directly on river banks (Figure 4(a)), with no structural protection against potential floods. Other components influencing social vulnerability, such as

Figure 4 GLOF vulnerability issue in the Cordillera Blanca, Peru. (a) Inappropriately located buildings on the confluence of the Quilcay River and Cojup Stream, Nueva Florida, Huaráz, Peru; (b) shows a transmission tower of the early warning system installed in the Chucchun Valley to warn the inhabitants of Carhuaz of a glacial lake outburst flood (GLOF) from Lake No. 513.

preparedness [early warning system (EWS), insurance, emergency plans, degree of awareness], prevention (urban planning) and response, also have a certain potential for improvement (Carey, 2005; Hegglin and Huggel, 2008).

The case study presented by Hegglin and Huggel (2008) revealed that the main constraints lie in institutional, political and economic limitations, and in the limited interest of the regional government. On the other hand, some vulnerability mitigation projects have been implemented with international co-operation (Reynolds, 2003; Carey *et al.*, 2012b). One of the latest examples is an EWS in the Chucchun Valley (Figure 4(b)), implemented after the 2010 GLOF as a result of the co-operation between the University of Zürich, the Glaciology Unit of ANA, and the Provincial Municipality of Carhuaz. This system includes automatic cameras, geophones, discharge measurements, and a meteorological station and is intended to warn the inhabitants of Carhuaz of a GLOF from Lake No. 513 (Huggel *et al.*, 2012; Schneider *et al.*, 2012).

Limitations of methods and data used

The first-order susceptibility assessment method presented by Emmer and Vilímek (2014) is used, which combines relatively low demands on input data but allows for a retrospective and repeatable assessment based on available historical data. This method is, by its nature, partly based on expert assessment but provides an instructive guide allowing repeatable use and should therefore provide identical results even for different assessors (in the case that identical input data are used). Previous verification of the method on the lakes of the Cordillera Blanca, performed by Emmer and Vilímek (2014), showed fairly good functionality of the method, successfully identifying lakes susceptible to outburst flood.

Input data from different sources have been used for the susceptibility assessment (see section *Input data*), resulting in variations in the accuracy of the parameters used. Nevertheless, varying accuracy of input data should not significantly influence the results or the generally observed trends. To evaluate the effectiveness of the implemented remedial works as reliably as possible, we used input data from the periods closest to the year of implementation of the remedial works for each lake. The date of data acquisition (see Table A1) should always be taken into consideration when interpreting the results. In the case of a longer lag time between the acquisition date of data for a pre- and post-remediation susceptibility assessment, natural environmental changes may also be assessed (e.g. rapid glacier retreat at Lake No. 513; see Table A1); however, such cases are in the insignificant minority.

Conclusions

Our investigation showed that remedial works implemented in the glacial lakes of the Cordillera Blanca represent an effective tool for hazard mitigation of glacial lake outburst floods and therefore also for risk management. However, it is highly important to (1) reliably identify hazardous lakes; (2) identify potential causes and mechanisms (scenarios) of outburst floods; and (3) select the most financially and technologically effective type of remediation.

We have shown that concrete open cuts decrease the susceptibility of the studied lakes to outburst floods following dam failure in the case of moraine dams but do not influence the susceptibility to outburst floods following dam overtopping. Artificial dams providing a certain freeboard and tunnels lowering water levels decrease the susceptibility of the studied lakes to outburst floods following dam overtopping. Tunnels conserving the original water level do not influence the susceptibility to any of the defined flood scenarios. Different types of remedial works are therefore suitable for the mitigation of different causes and mechanisms (scenarios) of potential floods, which need to be considered in hazard mitigation. On the other hand, it is important to realise that the implementation of any type of remedial works cannot completely eliminate the threat of GLOFs, as shown by recent GLOFs from previously remediated lakes. Rapid evolution of the high-mountain environment may cause significant changes in the susceptibility of a given lake (also remediated lake) to outburst floods over time. Thus, continuous monitoring and susceptibility assessment is recommended. While GLOF hazard mitigation is on a good level in the Cordillera Blanca, social vulnerability still remains an open issue.

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Appendix

Table A1 Pre-remediation input data

Characteristic (input data)	Lake									References
	Arhueycocha	Cochca	Ishinca	No. 513	Milluacocha	Palcacocha	Parón	Rajucolta	Safuna Alta	
Dam type	Moraine clam	Moraine dam	moraine dam	Bedrock/ moraine dam	Moraine dam	Moraine dam	Moraine dam	Moraine dam	Moraine dam	Investigated during FS, deduced from RSI (A)
Distance between the lake and glacier (m)	0	0	0	0	0	0	1400	0	0	Measured from RSI (A)
Maximal lake width (m)	400	260	360	380	335	220	NN	520	420	Measured from RSI (A)
Width of calving front (m)	275	40	450	450	200	250	NA	270	450	Measured from RSI (A)
Mean slope between lake and glacier (°)	NA	NA	NA	NA	NA	NA	33			Calculated from TM
Mean slope of last 500 m of glacier tongue (°)	NN	NN	NN		NN	NN	23	23		Calculated from TM
Maximal slope of moraines surrounding the lake (°)	60	50	35		80	72	40	45	70	FS; Hubbard *et al*. (2005)
Maximal slope of distal face of the dam (°)	32	9	25		15	10	18	23	50	FS; Cochachin *et al*. (2010): Cochachin and Torres (2011)
Lake area (m^2)	NN						NN	515 000	85 000	Hubbard *et al*. (2005): Cochachin *et al*. (2010)
Dam freeboard (m)	0	0	0	0	0	0	0	0	41	Hubbard *et al*. (2005)
Lake perimeter (m)	NN		NN		NN		NN	3600	1550	Measured from RSI (A), RSI (S)
Mean slope of lake surrounding (°)	NN		NN		NN		NN		60	Hubbard *et al.* (2005)
Dam width (m)	450	75	420		830	160	500	190	420	Measured from RSI (A), RSI (S)
Dam height (m)	170	5	165		200	23	95	40	165	FS; Cochachin *et al*. (2010); Cochachin and Torres (2011)
Piping	No	No	No	No	No	Yes	No	No	Yes	FS: Cochachin *et al*. (2010): Cochachin and Torres (2011)
Piping gradient (°)	NA					11			18	Measured during FS, calculated from TM
Remedial work	No	No	No	No	No	No	No	No	No	

Table A2 Post-remediation input data

Characteristic (input data)	Lake									References
	Arhueycocha	Cochca	Ishinca	No. 513	Milluacocha	Palcacocha	Parón	Rajucolta	Safuna Alta	
Dam type	Moraine dam	Moraine dam	Moraine dam	Bedrock dam	Moraine dam	Moraine dam	Moraine dam	Moraine dam	Moraine dam	Investigated during FS, deduced from RSI (A)
Distance between the lake and glacier (m)	0	0	0	**155**	0	0	1400	0	0	Measured from RSI (A), RSI (S)
Maximal lake width (m)	400	260	340	NN	**320**	220		**510**	420	Measured from RSI (A), RSI (S)
Width of calving front (m)	270	40	450	NA	200	250		**250**	450	Measured from RSI (A), RSI (5)
Mean slope between lake and glaicer (°)	NA	NA	NA	80			33			Calculated from TM
Mean slope of last 500 m of glacier tongue (°)	NN	N′	NN	26			23			Calculated from TM
Maximal slope of moraines surrounding the lake (°)	60	50	35		80	72	40	45	70	FS: Hubbard *et al.* (2005): Cochachin *et al*. (2010): Cochachin and Torres (2011)
Maximal slope of distal face of the dam (°)	32	9	25		15	**8**	18	**10**	50	FS; Cochachin *et al*. (2010); Cochachin and Torres (2011)
Lake area (m^2)			87 902	207 585		66 800	900 000	**513 000**	85 000	Cochachin *et al*. (2010); Cochachin and Torres (2011)
Dam freeboard (m)	0	0	**5**	**20**	0	**8**	**52**	**14**	**41**	FS: Cochachin *et al*. (2010): Cochachin and Torres (2011): Hubbard *et al.* (2005); Reynolds (2003)
Lake perimeter (m)		NN	1650	2250		1150	6500	3555	1550	Measured from RSI (S)
Mean slope of lake surrounding (°)		NN	15	65		60	30	35	60	FS; calculated from (TM)
Dam width (m)	450	75	270	NN	830	160	500	190	420	Measured from RSI (A), RSI (S)
Dam height (m)	162	**2**	**70**	NN	**194**	**20**	95	30	165	FS; Cochachin *et al*. (2010); Cochachin and Torres (2011)
Piping	No	No	No	No	No	Yes	No	No	Yes	FS, deduced from RSI (S)
Piping gradient (°)		NA				**6**			18	Measured during FS, calculated from TM

Table A2 Continued

Characteristic (input data)	Lake									References
	Arhueycocha	Cochca	Ishinca	No. 513	Milluacocha	Palcacocha	Parón	Rajucolta	Safuna Alta	
Remedial work			Artificial cut	Tunnel bedrock dam		Open cut, dams	Tunnel through the surrounding of the lake	Open	Tunnel through the moraine dam	FS; Cochachin *et al*. (2010); Cochachin and Torres (2011); Hubbard *et al*. (2005); Reynolds (2003)

List of input data used for assessing the pre- and post-remediation susceptibility of the nine studied lakes. Parameters that changed between the pre- and post-remediation susceptibility assessment are highlighted in bold (changes directly related to the implementation of remedial works are highlighted in green, while changes related to natural geo-environmental changes are in violet).NN, not needed for the assessment; NA, not available information for the particular lake (dam) type. References: FS, field survey; RSI (A), remotely sensed images (aeria); RSI (S), remotely sensed images (satellite); TM, topographical maps.

