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# 882 lakes of the Cordillera Blanca: An inventory, classification, evolution and assessment of susceptibility to outburst floods

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ABSTRACT

An inventory of the lakes within the Cordillera Blanca of Peru was made based on manual analysis of high resolution optical images and was verified during field surveys. In total, 882 lakes were detected, classified and described by several qualitative and quantitative characteristics. The majority of the lakes were characterised as moraine-dammed lakes (35.2%), followed by bedrock-dammed lakes (31.3%), while ice-dammed and landslide-dammed lakes were quite rare with 3.5% and 2.6%, respectively. Two thirds of the lakes (66.5%) have a surface area < 10,000 $m^2$ and are classified as being small, while only 7.3% are classified as large lakes with an area > 100,000 $m^2$. The majority of the large lakes are characterised as moraine-dammed lakes (48.4%) and the share of landslide-dammed lakes is significantly increased to 12.4% in this class. In the 1950s, most lakes were situated in the elevation range of 4250–4600 a.s.l. (Concha, 1951), while 49.4% of the lakes are currently situated above 4600 m a.s.l. This elevational shift is considered to be a result of ongoing environmental change and glacier retreat within the Cordillera Blanca. By analysing multi-temporal aerial images covering the period from 1948 to 2013 it was shown that glacial lakes in already deglaciated catchments may persist for long periods of time without any areal change. It was also shown that glacial lake outburst floods (GLOFs) originated from moraine-dammed lakes in the earlier stages of glacier retreat (1940s and 1950s) and from bedrock-dammed lakes in later stages (recently); however, no clear trend was revealed regarding the starting elevation of GLOFs. The susceptibility of all of the large lakes ($n = 64$) to outburst floods was assessed. Monitoring of young proglacial lakes and large moraine-dammed lakes, systematic susceptibility reassessments considering potential future changes, and flood modelling are recommended.



## 1. Introduction

High mountain areas are considered to be among those environments with the most sensitive response to climate change and consequently among the environments with the highest environmental dynamics (e.g., Evans and Clague, 1994; Clague et al., 2012; Huggel et al., 2015). Climate change, repeated alteration of the periods of glacier advance and consequent glacier retreat is leading to long-term environmental changes. In the framework of the general environmental change, different types of high mountain lakes form, evolve and also become extinct in a successive non-catastrophic or catastrophic way (e.g., Costa and Schuster, 1988; Clague and Evans, 2000; Korup and Tweed, 2007; Clague and O'Connor, 2014). Better knowledge of the distribution and evolutionary patterns of high mountain lakes and an understanding of the associated processes are of great scientific importance and have the potential to: (i) help in effective water management – a need resulting from changing hydrological conditions in glacierized watersheds (e.g., Mark and Seltzer, 2003; Mark et al., 2005; Pouyaud et al., 2005; Juen et al., 2007; Kaser et al., 2010; Nolin et al., 2010; Chevallier et al., 2011; Baraer et al., 2012; Carey et al., 2012a; Condom et al., 2012; Bury et al., 2013; Drenkhan et al., 2015; Lasage et al., 2015); (ii) help in the hazard analysis and risk management of lake outburst floods (e.g. Grabs and Hanisch, 1993; Reynolds, 2003; Kattelmann, 2003; Carey, 2005; Bolch et al., 2008; Carey et al., 2012b; Emmer and Vilímek, 2013, 2014); and (iii) retroactively help to better understand

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ongoing environmental change (Byers, 2000; Korup and Tweed, 2007; Carrivick and Tweed, 2013; Anacona et al., 2015; Emmer et al., 2015b).

### 1.1. Studied region and previous research

The Cordillera Blanca (8°–10°S; 77°–78° W; herein defined by the border of the Huascarán National Park; i.e. 3400 $km^2$) is a part of the western Peruvian Andes (Fig. 1), and hosts the majority of tropical glaciers worldwide (Ames and Francou, 1995). Glacier extent is, nevertheless, changing rapidly (e.g., Hastenrath and Ames, 1995; Kaser, 1999; Kaser and Georges, 1999; Georges, 2004; Casassa et al., 2007; Vuille et al., 2008; Jomelli et al., 2009; Rabatel et al., 2013; Schauwecker et al., 2014; Duran-Alarcon et al., 2015). The glacierized area was reconstructed to be 800–850 $km^2$ in the 1930s (Georges, 2004) whereas in 2010 it was 482 $km^2$ (Burns and Nolin, 2014). Official numbers of Unidad de Glaciologia y Recursos Hidricos, Autoridad Nacional del Agua (UGRH, ANA) report 472 $km^2$ in 2012. Such intense glacier retreat and the associated processes have led to: (i) the formation, evolution and extinction of different types of high mountain lakes; (ii) changing susceptibility of the lakes to outburst floods over time.

Research related to the high mountain lakes of the Cordillera Blanca goes back to a long history, beginning with the catastrophic dam failures of lakes Palcacocha and Yircacocha in 1941, which resulted in a large number of fatalities in the city of Huaráz (Broggi, 1942; Oppenheim, 1946; Concha, 1952). Attempts to prevent such disasters have led to the foundation of the Peruvian Research Institute (currently called Autoridad Nacional del Agua, ANA), which is located in Huaráz. A substantial number of reports have been produced and stored in the ANA library in Huaráz (e.g., Morales, 1966; Caceres, 1974; Portocarrero, 1984). As a result of continuous monitoring and field-based hazard investigation, more than forty lakes have been remediated by the implementation of various structural measures since the 1950s (e.g., Lliboutry et al., 1977; Reynolds, 2003; Carey, 2005, Portocarrero, 2014; Emmer et al., 2016a). Recent events have documented that such attempts have strongly reduced the risks, however not to zero (Carey et al., 2012b; Emmer et al., 2014).

A number of case studies investigating individual lakes and/or outburst floods in the Cordillera Blanca have been published over the last decade and reflect the scientific importance of this topic (see Vilímek et al., 2014a; Emmer et al., 2016b). These include the works of Vilímek et al. (2005) focusing on Lake Palcacocha and the outburst flood of 2003, Hubbard et al. (2005) focusing on Lake Safuna Alta and the outburst flood of 2002; Carey et al. (2012b), Valderrama and Vilca (2012), Klimeš et al. (2014) and Vilímek et al. (2015) focusing on Lake No. 513 and the outburst flood of 2010 and Iturrizaga (2013) and Emmer et al. (2015a) focusing on the Jatunraju glacier and Lake Parón. Several papers also directly deal with the issue of hazard or vulnerability assessment (Reynolds, 2003; Carey, 2005; Hegglin and Huggel, 2008; Mark et al., 2010; Bury et al., 2011; Emmer and Vilímek, 2013; Schneider et al., 2014; Emmer and Vilímek, 2014; Rivas et al., 2015; Somos-Valenzuela et al., 2016).

The first inventory and typology of the lakes of the Cordillera Blanca was made by Concha (1951), who mentioned 230 lakes of 'significant size' and provided a basic classification scheme. These figures were revised by CCLCB (1967) mentioning 160 lakes, including the indication of dangerous lakes, Morales et al. (1979) mentioning 267 lakes of 'significant size' in 1970, Portocarrero (1995) mentioning 899 lakes and Cochachin and Torres (2011) mentioning 834 lakes with $A > 5000$ $m^2$ using automatic remotely sensed images-based detection. Vilímek et al. (2016) recently summarised 2370 lakes of all sizes, and Iturrizaga (2014) presented a conceptual approach to investigate the spatiotemporal distributional patterns of lake types in the Cordillera Blanca. Nevertheless, none of these recent works provide a more detailed overview of the characteristics of the individual lakes and their evolutionary patterns in the broader context of ongoing environmental change, including hazard evaluation.

### 1.2. Objectives of the study

The main objectives of this study are: (i) to provide a comprehensive inventory of the lakes within the Cordillera Blanca of Peru, including a basic quantitative as well as qualitative description of each lake; (ii) to analyse these characteristics especially in relation to the lake type and between each other; (iii) to analyse the evolution of the lakes over time with special emphasis given to the longevity of the lakes situated within deglaciated catchments; (iv) to assess the susceptibility of large lakes to outburst floods. The work should therefore help to fill the gap in the general knowledge on the lakes of the Cordillera Blanca facing ongoing environmental change and provide implications for lake outburst hazard management through an approach possibly applicable elsewhere in high mountain areas.

## 2. Data and methods

### 2.1. Data

High resolution optical remotely sensed images (see Table 1) were used for lake detection, classification and description (see Section

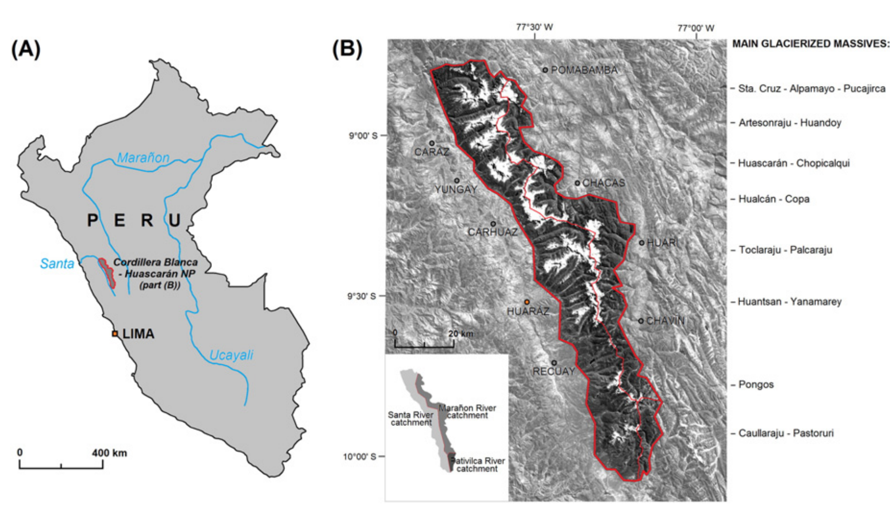


**Fig. 1.** The study area. (A) shows the localisation of the study area within Peru. (B) shows the study area on a Landsat image.

**Table 1**
An overview of the data used.

| Remotely sensed (RS) images | | Topographical data | Documentary data | Field data |
|---|---|---|---|---|
| Aerial photos | Satellite images | | | |
| Three sets: 1948, 1962, 1970 | CNES, Astrium, Landsat images (1970–2014) available at Google Earth Digital Globe PRO 2014 | COFOPRI topographical maps 1:25,000; Alpenverein maps 1:100,000; SRTM DEM, Google Earth Digital Globe PRO 2014 | Reports from ANA archive, Huaráz, Peru | Detailed topographical measurements, reconnaissance and mapping |

2.2.1). These include historical aerial photos and recent satellite images covering the period since 1948. Historical aerial photos used for the analysis (sets 1948, 1962 and 1970) were all taken during dry season and are, therefore, considered comparable for the analysis (see Section 3.2). The most up-to-date satellite images (CNES, Astrium) covering the entire area of the Cordillera Blanca are dated 2013 or earlier. Lake names were gathered from topographical Alpenverein maps 1:100,000 (Alpenvereinskarte, 2005; Alpenvereinskarte, 2006). Some data from unpublished reports from the library of Autoridad Nacional del Agua (ANA, Huaráz, Peru) were used for the susceptibility assessment, as well as data gathered during field surveys performed at selected sites between 2012 and 2015.

## 2.2. Methods

### 2.2.1. Lake detection, classification and surveyed characteristics

The lakes of the Cordillera Blanca were detected and classified based on a manual analysis of up-to-date (taken in 2013 or later) high resolution optical remotely sensed images (see Table 1). Only the lakes exceeding a threshold dimension were considered. The size criterion for consideration was defined based on lake length/lake width relation as follows:

$$Ll + Lw > 100\text{ m and } Lw > 20\text{ m} \quad (1)$$

where Ll is lake length in m and Lw is lake width in m. Spatially delimited groups of small supraglacial lakes were considered regardless of the size criterion. Each detected lake was then characterised by several quantitative as well as qualitative characteristics (see Table 2).

We used five classes of main lake types according to the material of the dam, reflecting slightly modified concepts of Emmer et al. (2014) and Iturrizaga (2014). The class of 'landslide-dammed lakes' includes all lakes dammed by deposition of different types of slope movements (landslides, rockslides, debris flows), the class of 'ice-dammed lakes' includes supraglacial and glacier-dammed lakes, and the class of 'moraine-dammed lakes' includes all subtypes of moraine dams (moraine-dammed lakes and moraine ponds according to Iturrizaga (2014)). The class of 'bedrock-dammed lakes' includes lakes filling overdeepings in bedrock, irrespective of its origin (glacial or structural). In a strict sense, these are not 'dammed' lakes, but lakes occupying overdeepings, or so-called 'embedded lakes' (sensu Mergili and Schneider (2011)). The class of 'combined dams' refers to such dams composed of two or more distinct parts (mostly bedrock depression with moraine cover, increasing dam height, lake depth and volume). An additional class of 'not specified lakes' includes lakes that were unclassifiable, ambiguous or the low quality of the image did not allow for lake classification.

### 2.2.2. First-order assessment of susceptibility to outburst floods

Large lakes are particularly interesting for the local authorities and simultaneously required input data for susceptibility assessment are available (see also ANA reports; Cochachin et al., 2010; Cochachin and Torres, 2011; UGRH, 2014, 2015). Therefore, a slightly modified version of the method for assessing the susceptibility of glacial lakes to outburst floods presented by Emmer and Vilímek (2014) was applied to large ($A > 100{,}000\ m^2$) glacial lakes and dimensionless blockage index (DBI) developed by Ermini and Casagli (2003) was applied to large landslide-dammed lakes (see below). This method was chosen because it was directly designed for the lakes of the Cordillera Blanca and accounts for its regional specifics (Emmer and Vilímek, 2013); in addition it is easily repeatable and reproducible. This method is based on a combination of decision trees and simple numerical calculations (see also e.g., Huggel et al., 2004) and provides five separate results (potentials) for five different GLOF scenarios: (i) dam overtopping resulting from a fast slope movement into the lake (scenario 1), (ii) dam overtopping following the flood wave originating in a lake situated upstream (scenario 2), (iii) dam failure resulting from a fast slope movement into the lake (scenario 3), (iv) dam failure following the flood wave originating in a lake situated upstream (scenario 4), and (v) dam failure following a strong earthquake (scenario 5). The potential for each scenario is expressed by an index in the range 0–1.

In the original methodology, all of the upstream situated lakes with >5% of the area of the assessed lake are considered in the scenarios 2 and 4. In this paper, only the upstream situated lakes with an area fitting into the class of 'large' are considered for the scenarios because of the high number of assessed lakes and the demands on input data (17 input characteristics for each of the assessed lakes). Ice avalanches into the lake are considered as a potential trigger only when (i) the distance between the lake and the glacier <1000 m, or (ii) the slope between the lake and the glacier >26.6° (sensu Alean, 1985). Moraine slopes steeper than 35° are considered as being potential starting zones for landslides (sensu Vilímek et al., 2014b).

In the case of landslide-dammed lakes, a widely used dimensionless blockage index (DBI) as defined by Ermini and Casagli (2003) is calculated first in order to assess the stability of the landslide dams. The subsequent procedure of the susceptibility assessment is similar to glacial lakes. DBI is defined as follows:

$$DBI = \log(A_b \cdot H_d / V_d) \quad (2)$$

where $A_b$ is the catchment area in $m^2$, $H_d$ is the dam height in m a $V_d$ is the estimated dam volume in $m^3$.DBI was used to quantify the stability of the dam. Based on analysis of large set of events, landslide dams are considered to be stable domains when DBI < 2.75; uncertain domains when DBI A ∈ ⟨2.75, 3.08⟩ and unstable domains when DBI > 3.08 in this approach (Ermini and Casagli, 2003). Dams of lakes with combined dams (bedrock dam with thin moraine cover) were considered as stable structures and only the potentials for scenarios 1 and 2 were assessed. Based on a validation of the susceptibility assessment method (Emmer and Vilímek, 2014), the resulting susceptibility to outburst floods is expressed in four classes: (i) zero or residual; (ii) low; (iii) medium; and (iv) high (see Table 3), because the numerical results of the calculations for the different scenarios are not comparable. In addition, the low number of recorded events prevents an estimation of the critical value for the scenario 4.

# 3. Results

## 3.1. Spatial distribution and lake characteristics

### 3.1.1. Qualitative characteristics

A total of 882 lakes are detected (see Appendix I), of which 60.7% ($n = 535$) are located within the catchment of the Santa River, 32.3%

**Table 2**
Characteristics of each lake.

| Description | | Data used | Value |
|---|---|---|---|
| Qualitative characteristics: | | | |
| ID number | Identification number | – | 1 to 882 |
| Name | – | Alpenverein map 1:100,000, ANA reports | Lake name |
| Lake type | Lake type according to the dam material, modified from Emmer et al., 2014 and Iturrizaga, 2014 | RS images | (i) Landslide-dammed lake;<br>(ii) Ice-dammed lake;<br>(iii) Moraine-dammed lake;<br>(iv) Bedrock-dammed lake;<br>(v) Combined dam lake;<br>(vi) Not specified lake type |
| Lake outflow | Surface outflow | RS images, ANA reports | (i) YES (lakes with clearly recognisable surface outflow);<br>(ii) NO (lakes without recognisable surface outflow) |
| Lake/glacier relation | Spatial relation lake-glacier | RS images | (i) Lakes in direct contact with glacier (proglacial lakes);<br>(ii) Lakes, which are no more in direct contact with glacier but still have some glaciers in their catchment;<br>(iii) Lakes, which do not have any glaciers in their catchment (lakes in deglaciated catchments) |
| Catchment | Assignment of lake to one of the three main catchments | Alpenverein map 1:100,000 | (i) Santa River (Pacific Ocean)<br>(ii) Pativilca River (Pacific Ocean)<br>(iii) Marañón River (Atlantic Ocean) |
| Lake(s) situated upstream | Position of the lake in the cascade system | RS images, Alpenverein map 1:100,000 | (i) YES (lakes with some lake(s) situated upstream);<br>(ii) NO (lakes with no lake(s) situated upstream) |
| Remedial works | Implementation of remedial works | ANA reports, field survey | (i) YES (some type of remedial work has been implemented);<br>(ii) NO (no remediation) |
| Outburst flood | Occurrence of a lake outburst flood in the past | ANA reports, geomorphological evidence (e.g. erosion x accumulation) derivable from RS images | (i) YES (outburst flood has been documented);<br>(ii) NO (no outburst flood documented) |
| Quantitative characteristics: | | | |
| Latitude | WGS84 latitude | Alpenverein map 1:100,000, Google Earth Digital Globe PRO 2014 | Continuous variable (°S) |
| Longitude | WGS84 longitude | Alpenverein map 1:100,000, Google Earth Digital Globe PRO 2014 | Continuous variable (°W) |
| Elevation | Elevation of the lake water level | Alpenverein map 1:100,000, reports from ANA archive, Google Earth Digital Globe PRO 2014 | Continuous variable (m a.s.l.) |
| Lake size | Lake surface area | RS images | Continuous variable, three classes were defined:<br>(i) small lakes ($A < 10{,}000$ m$^2$);<br>(ii) medium lakes ($A \in \langle 10{,}000, 100{,}000 \rangle$ m$^2$);<br>(iii) large lakes ($A > 100{,}000$ m$^2$) |

($n = 284$) within the catchment of the Marañón River, and 7.1% ($n = 63$) within the catchment of the Pativilca River. Most of the detected lakes are classified as moraine-dammed lakes (see Table 4) with a 35.3% ($n = 311$) share, followed by bedrock-dammed lakes (31.3%; $n = 276$) and lakes with combined dams (15.9%; $n = 140$). Landslide-dammed lakes (2.6%; $n = 23$) and ice-dammed lakes (3.5%; $n = 31$) are less common. The lake type of the remaining 101 lakes (11.4%) is not specified. Surface outflow (dam freeboard 0 m) is clearly recognisable in the case of 69.8% ($n = 616$) of the lakes, but there are significant differences between the individual lake types. A higher share of and slide-dammed lakes and bedrock-dammed lakes displays surface outflow (87.0% ($n = 20$) and 83.3% ($n = 230$), respectively). >These numbers contrast to only 62.7% ($n = 195$) for moraine-dammed lakes and 0.0% for ice-dammed lakes. The absence of surface outflow is mainly caused by: (i) piping/seepage through the dam (moraine-dammed lakes, landslide-dammed lakes); (ii) drainage through the subglacial/englacial channels (ice-dammed lakes); or (iii) insufficient water inflow into the lake (all lake types).

Only 30.2% ($n = 266$) of the lakes have another lake situated upstream within the catchment, acting as a potential trigger of a lake

**Table 3**
Classification of the results of the susceptibility assessment into the four classes for five outburst flood scenarios (modified from Emmer and Vilímek, 2014).

| Susceptibility to outburst floods | Outburst flood scenario | | | | |
|---|---|---|---|---|---|
| | Scenario 1 | Scenario 2 | Scenario 3 | Scenario 4 | Scenario 5 |
| Zero or residual (0) | <0.200 | [a] | < 0.100 | [a] | <0.050 |
| Low (+) | 0.200 to 0.499 | [a] | 0.100 to 0.199 | [a] | 0.050 to 0.149 |
| Medium (++) | 0.500 to 0.899 | [a] | 0.200 to 0.499 | [a] | 0.150 to 0.199 |
| High (+++) | >0.899 | [a] | > 0.499 | [a] | >0.199 |

[a] Depending on the outburst scenario (and the resulting susceptibility (0/+/++/+++) of lakes situated upstream).

**Table 4**
Selected qualitative characteristics of the studied lakes.

| | Number | Surface outflow | | Lake/glacier relation | | | Lake(s) upstream | |
|---|---|---|---|---|---|---|---|---|
| | | YES | NO | DC | SG | NG | YES | NO |
| Cordillera Blanca overall | 882 | 616 (69.8%) | 266 (30.2%) | 75 (8.5%) | 357 (40.5%) | 450 (51.0%) | 266 (30.2%) | 616 (69.8%) |
| Landslide-dammed lakes | 23 (2.6%) | 20 (87.0%) | 3 (13.0%) | 0 | 10 (43.5%) | 13 (56.5%) | 15 (65.2%) | 8 (34.8%) |
| Ice-dammed lakes | 31 (3.5%) | 0 | 31 (100%) | 31 (100%) | 0 | 0 | 2 (6.5%) | 29 (93.5%) |
| Moraine-dammed lakes | 311 (35.3%) | 195 (62.7%) | 116 (37.3%) | 13 (4.2%) | 179 (57.5%) | 119 (38.3%) | 104 (33.3%) | 207 (66.7%) |
| Bedrock-dammed lakes | 276 (31.3%) | 230 (83.3%) | 46 (16.7%) | 25 (9.0%) | 102 (37.0%) | 149 (54.0%) | 75 (27.2%) | 201 (72.8%) |
| Combined-dam lakes | 140 (15.9%) | 100 (71.4%) | 40 (28.6%) | 6 (4.3%) | 49 (35.0%) | 85 (60.7%) | 42 (30.0%) | 98 (70.0%) |
| Not specified lakes | 101 (11.4%) | 71 (30.3%) | 30 (29.7%) | 0 | 17 (16.8%) | 84 (83.2%) | 28 (27.3%) | 73 (72.3%) |

Relation to lake glacier: DC – direct contact (proglacial lakes); SG – some glaciers situated in the catchment of the lake; NG – no glaciers situated in the catchment of the lake.

outburst flood; nevertheless, this figure increases rapidly considering lake size i.e. 41.1% ($n = 95$) of medium size lakes (see Section 3.1.2) and 65.5% ($n = 42$) of large size lakes have one or more lake(s) situated within the catchment. These figures are expected to change with future glacier retreat and formation of new lakes (e.g., Colonia et al., 2015; Haeberli et al., 2016), which in turn, may change degree of susceptibility to outburst floods. Another characteristic related to the susceptibility of the given lake to outburst floods is the relation between the lake and the glacier. A slight majority of lakes (50.9%; $n = 449$) have no glaciers within their catchment, while 40.6% ($n = 358$) have some glaciers within their catchment and only 8.5% ($n = 75$) have direct contact with the glacier (proglacial lakes). Again, there are some differences between individual lake types. An overall number of 50 lakes (5.7%) have been remediated by implementing open cuts, artificial dams or tunnels (e.g., Reynolds, 2003; Carey, 2005; Portocarrero, 2014) or equipped with some kind of water management measures (e.g., sluice gate). These measures are considered to be an effective tool for lake outburst flood hazard mitigation and water management (Portocarrero, 2014; Emmer et al., 2016a).

#### 3.1.2. Quantitative characteristics

The basic statistics of the quantitative characteristics of the studied lakes are presented in Table 5. Three classes of lake size (small ($A < 10{,}000$ m$^2$); medium ($A \in <10{,}000,\ 100{,}000>$ m$^2$); and large ($A > 100{,}000$ m$^2$)), and four classes of lakes according to elevation (ELEV <4000 m a.s.l.; ELEV ∈ <4000, 4500> m a.s.l.; ELEV ∈ <4500, 5000> m a.s.l.; and ELEV >5, 000 m a.s.l.)), as defined in Table 1, have been analysed in relation to the lake type. It emerged that the majority of the detected lakes regardless of lake type are of a small size (66.5%; $n = 587$) and only 64 lakes (7.3%) are classified as large lakes. In the case of all the studied lake types, the number of lakes of a given size naturally decreases with increasing size. The only exception is represented by landslide-dammed lakes, many of which (34.8%; $n = 8$) are classified as large lakes.

From the point of view of elevational distribution, the majority of the detected lakes (62.1%; $n = 548$) are situated at the elevational zone of 4500–5000 m a.s.l. It emerged that landslide-dammed lakes significantly differ from other lake types, with 39.1% ($n = 9$) of landslide-dammed lakes being situated at an elevation of below 4000 m a.s.l. and 91.3% ($n = 21$) being situated below 4500 m a.s.l. The majority of large lakes (78.1%; $n = 50$) are situated below 4600 m a.s.l.; however, this state is not definite and ongoing environmental change also contributes to its dynamics (see Fig. 2; Section 4.2). A total of 42 large lakes (65.6%) are situated below 4500 m a.s.l.

### 3.2. Temporal analysis

The general life cycle of lakes in high mountains with re-advancing glaciers may be divided into three phases: **glacier advance**, **glacial retreat** ('proglacial' and 'glacier-detached' sub-phases) and **nonglacial** (see Emmer et al., 2015b). Firstly, during the glacier advance phase, depressions in bedrock are intensively modelled (over-deepened), massive moraines are built, and ice-dammed lakes occupying tributary valleys blocked by advancing glaciers may form in the main valley (the last significant glacier retreat happened in the Cordillera Blanca between 1780 and 1880; Thompson et al., 2000; Solomina et al., 2007).

**Table 5**
Selected quantitative characteristics of studied lakes.

| | Number | Lake area | | | Elevation | | | |
|---|---|---|---|---|---|---|---|---|
| | | $A < 10{,}000$ m$^2$ | $A \in \langle 10{,}000, 100{,}000\rangle$ m$^2$ | $A > 100{,}000$ m$^2$ | ELEV < 4000 m a.s.l. | ELEV ∈ ⟨4000, 4500⟩ m a.s.l. | ELEV ∈ ⟨4500, 5000⟩ m a.s.l. | ELEV > 5000 m a.s.l. |
| Cordillera Blanca overall | 882 | 587 (66.5%) | 231 (26.2%) | 64 (7.3%) | 18 (2.0%) | 288 (32.7%) | 548 (62.1%) | 28 (3.2%) |
| Landslide-dammed lakes | 23 | 8 (34.8%) | 7 (30.2%) | 8 (34.8%) | 9 (39.1%) | 12 (52.2%) | 2 (8.7%) | 0 |
| Ice-dammed lakes | 31 | 31 (100%) | 0 | 0 | 0 | 4 (12.9%) | 25 (80.6%) | 2 (6.5%) |
| Moraine-dammed lakes | 311 | 182 (58.5%) | 98 (31.5%) | 31 (10.0%) | 1 (0.3%) | 111 (35.7%) | 190 (61.1%) | 9 (2.9%) |
| Bedrock-dammed lakes | 276 | 175 (63.4%) | 85 (30.8%) | 16 (5.8%) | 0 | 73 (26.4%) | 189 (68.5%) | 14 (5.1%) |
| Combined-dam lakes | 140 | 101 (72.1%) | 32 (22.9%) | 7 (5.0%) | 0 | 37 (26.4%) | 100 (71.4%) | 3 (2.2%) |
| Not specified lakes | 101 | 90 (89.1%) | 9 (8.9) | 2 (2.0%) | 8 (7.9%) | 51 (50.5%) | 42 (41.6%) | 0 |

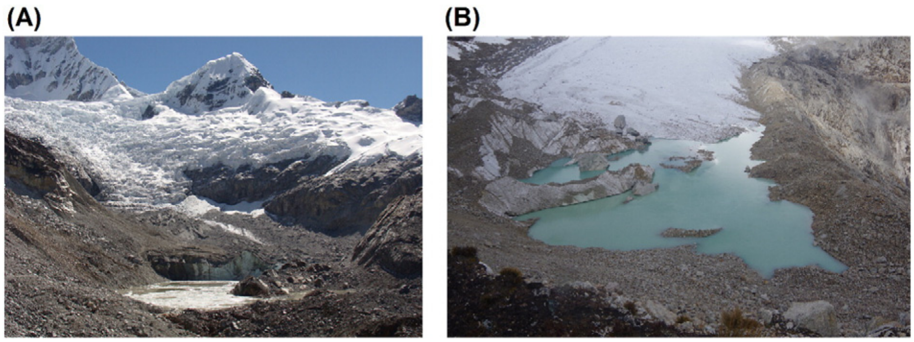


**Fig. 2.** Examples of localities, which host lakes with potential for further significant growth. (A) shows a rapidly growing lake on the south-eastern side of the Chopicalqui massif (6354 m a.s.l.) at an elevation of 4625 m a.s.l., lake area increased from 0.042 $km^2$ in 2003 to 0.094 $km^2$ in 2013 (+124%); (B) shows the initial state of the evolution of a bedrock-dammed lake on the southern side of the Artesonraju massif (6025 m a.s.l.) with a water level at an elevation of 4725 m a.s.l.

During the initial phase of glacier retreat, new lakes form in the elevation zone close to the retreating glacier tongues, replacing retreating glacier tongues behind terminal moraines and filling glacially-modelled depressions in the bedrock. A total of 432 lakes (49.0%) of the Cordillera Blanca currently have some glaciers in their catchments, of which 75 lakes (8.5% of all lakes) are in direct contact with the glaciers ('proglacial' sub-phase). The overall number of lakes as well as the overall number of lake outburst floods (all recorded GLOFs occurred in these catchments) generally increase in this phase (see also Emmer et al., 2015b).

During the final phase of glacier retreat, when the majority of glaciers are already melted away, lakes whose catchments are no longer occupied by glaciers may turn into seasonal or endorheic lakes, or may become extinct in a non-catastrophic way as a result of basin filling by sedimentation and/or losing their main source of water (see also Section 4.1). We detected 450 lakes (51.0% of all lakes), whose catchments are currently completely without glaciers (see Section 3.1.1). These lakes are more frequently represented within the catchment of the Marañón River (57.4%; $n = 163$), and especially within the catchment of the Pativilca River (84.1%; $n = 53$).

We also were able to identify 120 lakes with completely deglaciated catchments (current state) from archive aerial photographs from 1948 (67.5% with an area of up to 10,000 $m^2$ and 7.5% with an area over 100,000 $m^2$). Almost 92% ($n = 110$) of these lakes were already located in completely deglaciated catchments in 1948. A comparison of their areal extent with the current situation showed that only 5% ($n = 6$) of lakes whose catchment was without a glacier in 1948 experienced a reduction of their areal extent. In contrast, almost 16% ($n = 20$) of these lakes experienced an increase in their areal extent and the majority of them (70%; $n = 84$) underwent no detectable change. This analysis of the areal extent of the lakes in the final phase of glacier retreat suggests that lake extinction represented by lake area reduction is considerably delayed with respect to glacier retreat. In our case, 86% of the analysed lakes retained or increased their areal extent after at least 67 years in a deglaciated catchment. However, we have no information about the volume change of these lakes, which could be influenced by sedimentation leaving a similar areal extent of the lakes.

### *3.3. Susceptibility to outburst floods*

The susceptibility of 64 large lakes of the Cordillera Blanca to outburst floods has been assessed. Slightly different procedures for different lake types have been used (see Section 2.2.2). Glacial lakes represent the majority of the large lakes within the Cordillera Blanca with a 84.4% share ($n = 54$), of which 31 lakes are characterised as moraine-dammed lakes; 16 as bedrock-dammed lakes, and 7 as lakes with combined dams (bedrock + moraine). Almost two fifths of all of the large lakes (39.1%; $n = 25$), and especially large moraine-dammed lakes (54.5%; $n = 18$), have been remediated by the implementation of various structural measures, which are considered in the susceptibility estimation. The results of the DBI calculation showed that dams of all of the assessed large landslide-dammed lakes ($n = 8$) are considered to be a stable domain with DBI varying between 0.08 (extremely flat dam of Lake Tayanacocha terminating in a relatively small catchment) and 2.45 (debris cone-dammed Lake Llanganuco Bajo). Therefore, dam overtopping (scenarios 1 and 2) is considered to be the only possible mechanism of an outburst flood.

A detailed susceptibility assessment showed that 40 of the 64 large lakes (62.5%) are currently susceptible to outburst floods classified as low or higher (see Table 6), of which 25 lakes (39.1%) reached a score representing medium susceptibility to outburst floods (++) and four lakes (6.3%) reached high susceptibility to outburst floods (+++). These are Lake Jancarurish (ID 69), a nameless lake (ID 353), Lake Milluacocha (ID 366), and Lake Palcacocha (ID 398). The majority of the large lakes with low or higher susceptibility are susceptible to outburst floods following dam overtopping resulting from a fast slope movement into the lake (Scenario 1), five large lakes are susceptible to Scenario 2, nine large lakes are susceptible to Scenario 3, only one lake is susceptible to Scenario 4, and thirteen lakes are susceptible to Scenario 5.

## 4. Discussion

The discussion is structured into four parts of which the first three parts are focusing on longevity of lakes and relation to lake outburst floods (see Section 4.1), frame and manifestation of post-LIA environmental change (see Section 4.2) and implications for lake outburst flood hazard management (see Section 4.3). The methods and used data, the interpretation of the obtained results and potential sources of errors are discussed in Section 4.4.

### *4.1. Longevity of high mountain lakes and its relation to lake outburst floods*

Two general types of lakes have been detected within the study area from the point of view of dam stability:

-lakes impounded by potentially unstable natural dams (moraine, landslide or ice); and

-lakes impounded by stable bedrock dams (bedrock-dammed or 'embedded' lakes; see Section 2.1).

It was shown by Costa and Schuster (1988) and Ermini and Casagli (2003), that the longevity of potentially instable natural dams is generally in terms of a geological time-scale. Moraine, landslide and ice dams are often highly unstable temporal entities with a life span of $10^{-2}$ years in the case of extremely short lived ice-dammed and landslide-dammed lakes, and $10^4$ years in the case of large landslide-dammed lakes (Korup and Tweed, 2007). Lakes may become extinct:

(i) in a successive non-catastrophic way

**Table 6**
Large lakes susceptible to outburst floods and their potential triggers (0 - zero or residual susceptibility; + low susceptibility; ++ medium susceptibility; +++ high susceptibility).

| Lake (ID) | Outburst flood scenario | | | | |
|---|---|---|---|---|---|
| | Scenario 1 | Scenario 2 | Scenario 3 | Scenario 4 | Scenario 5 |
| Berónica (3) | 0 | 0 | 0 | 0 | ++ |
| Pucacocha (38) | + | 0 | 0 | 0 | 0 |
| Safuna Alta (42) | ++ | 0 | ++ | 0 | + |
| Safuna Baja (43) | ++ | ++ | 0 | + | + |
| Jancarurish (69) | +++ | 0 | + | 0 | 0 |
| Quitacocha (63) | ++ | 0 | ++ | 0 | + |
| Cullicocha (70) | 0 | ++ | 0 | 0 | 0 |
| Yuracocha (72) | ++ | 0 | 0 | 0 | + |
| Arhueycocha (94) | ++ | 0 | 0 | 0 | + |
| Tullicocha (95) | + | 0 | + | 0 | + |
| Parón (139) | ++ | 0 | + | 0 | 0 |
| Llanganuco Alto (160) | + | 0 | 0 | 0 | 0 |
| Llanganuco Bajo (163) | + | + | 0 | 0 | 0 |
| Huallcacocha (178) | ++ | 0 | 0 | 0 | + |
| Checquiacocha (181) | ++ | 0 | ++ | 0 | 0 |
| Auquiscocha (182) | ++ | ++ | 0 | 0 | 0 |
| Lake No. 513 (185) | + | 0 | 0 | 0 | 0 |
| Lajiacocha (188) | + | 0 | 0 | 0 | + |
| Pag Pag (197) | ++ | 0 | + | 0 | 0 |
| Yanaraju (209) | ++ | 0 | ++ | 0 | + |
| nameless (242) | + | 0 | 0 | 0 | 0 |
| Allicocha (243) | ++ | 0 | 0 | 0 | ++ |
| Paccharuri (344) | ++ | 0 | 0 | 0 | 0 |
| Pucaranra (351) | + | 0 | 0 | 0 | 0 |
| nameless (353) | +++ | 0 | 0 | 0 | 0 |
| Akilpo (360) | ++ | 0 | 0 | 0 | ++ |
| Milluacocha (366) | +++ | 0 | 0 | 0 | + |
| nameless (388) | + | 0 | 0 | 0 | 0 |
| Perolcocha (393) | ++ | 0 | 0 | 0 | 0 |
| Palcacocha (398) | +++ | 0 | 0 | 0 | 0 |
| Churup (414) | + | 0 | 0 | 0 | 0 |
| Cuchilla (425) | ++ | 0 | 0 | 0 | 0 |
| Tullpacocha (428) | ++ | 0 | ++ | 0 | 0 |
| Shallap (438) | ++ | 0 | 0 | 0 | 0 |
| Rajucolta (449) | ++ | 0 | 0 | 0 | 0 |
| Tararhua (470) | ++ | 0 | 0 | 0 | 0 |
| Maparaju (504) | ++ | 0 | 0 | 0 | 0 |
| Pamparaju (629) | ++ | 0 | 0 | 0 | 0 |
| Gueshguecocha (635) | 0 | ++ | 0 | 0 | 0 |

Scenario 1: dam overtopping resulting from a fast slope movement into the lake; Scenario 2: dam overtopping following the flood wave originating in a lake situated upstream; Scenario 3: dam failure resulting from a fast slope movement into the lake; Scenario 4: dam failure following the flood wave originating in a lake situated upstream; Scenario 5: dam failure following a strong earthquake.

-as a result of decreasing water inflow into the lake, following changes in precipitation patterns or hydrological conditions within the catchment (presence/absence of glaciers), which can both lead to endorheic conditions and the lake drying up,

-as a result of the lake being filled by sediment, being a function of the material influx into the lake (specific sediment influx and lake catchment area) and the volume of the lake basin,

-as a result of successive dam incision, without any lake outburst flood; or

(ii) in a catastrophic way (dam failure followed by a lake outburst flood; potentially unstable dams).

The short lifespan of the natural dams of the Cordillera Blanca is documented by a number of infilled lakes (Iturrizaga, 2014) and also by dam failures since the end of the Little Ice Age.

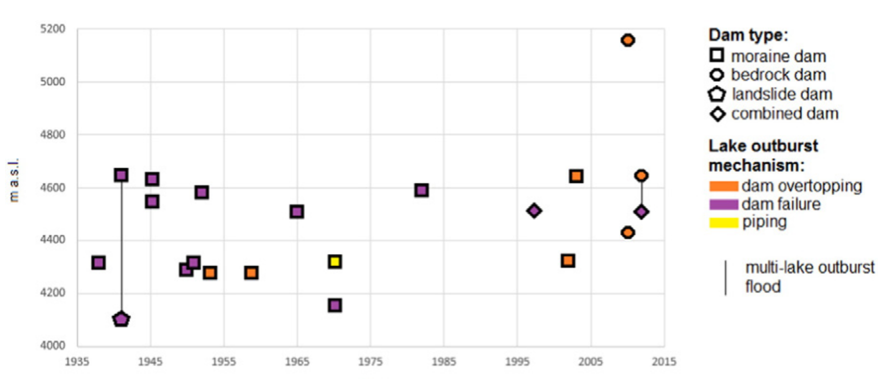


**Fig. 3.** Starting elevation of significant lake outburst floods (lake level elevations) recorded in the Cordillera Blanca and involved lake types. Data: Zapata (2002), Reynolds (2003), Emmer et al. (2014), this study.

In addition to generally unstable natural dams (41.4%, $n = 365$), bedrock-dammed lakes (31.3%, $n = 276$) are also common within the study area. These dams are considered to be stable and the lakes may only become extinct in a successive non-catastrophic way (see above). Nevertheless, lakes with stable dams may produce outburst floods, as a result of dam overtopping (e.g., dam overtopping of bedrock-dammed lake No. 513 in 2010; Carey et al., 2012a, b; Schneider et al., 2014; Vilímek et al., 2015). Lake outburst floods are considered a specific evolutionary pattern of high mountain lakes in the initial stages of warmer periods and glacier retreat (Clague and Evans, 2000) as well as significant geomorphological processes (Richardson, 2010). Tens of lake outburst floods (some of them repeated) have been documented within the relatively densely populated region of the Cordillera Blanca since the beginning of the 18th century (e.g., Ames, 1985; Zapata, 2002).

We analysed the temporal as well as spatial distribution of lake outburst floods and their relation to different lake types in order to identify regional patterns in the spatio-temporal distribution of these events. The number of outburst floods from landslide-dammed lakes is too low for analysis (2 cases), therefore only documented outburst floods from glacial lakes were analysed (15 cases). It emerged that there is no significant change in the starting elevation (see Fig. 3), ranging between 4300 and 4650 m a.s.l., with one exception of flood from an unnamed lake in Ishinca valley (starting elevation 5170 m a.s.l.). While all of the significant GLOFs in the 20th century originated in moraine-dammed lakes, GLOFs originating in bedrock-dammed lakes dominated in the beginning of 21st century. This phenomenon is in concordance with the hypothesis presented by Clague and Evans (2000), who proposed a high frequency of outburst floods from moraine-dammed lakes in earlier stages of deglaciation, while bedrock-dammed lakes have not yet evolved (see also Emmer et al., 2015b). It also emerged that the majority of the recorded events occurred during the 'proglacial' stage of lake evolution.

### 4.2. Lakes and environmental change in a post-LIA timeframe

Significant changes in the lake system are visible in the Cordillera Blanca in the last few decades. Concha (1951) pointed out that in the 1950s most of the lakes were situated in the elevational zone of 4250–4600 m a.s.l. In our inventory, 39.9% ($n = 352$) of lakes are situated within this elevational range, while 49.4% ($n = 436$) of lakes are situated above 4600 m a.s.l. We interpret this elevational shift to be part of the environmental change and ongoing glacier retreat within the Cordillera Blanca in the second half of the 20th century. This conclusion is in accordance with findings of Salerno et al. (2014) from the Southern Alps, Italy. Glacier retreat also leads to a shift in the share and distribution of different lake types in space and time. In the current state, the majority of lakes with potential for further growth (proglacial lakes excluding ice-dammed supraglacial lakes) are classified as bedrock-dammed lakes (56.8%; $n = 44$) and the minority as moraine-dammed lakes (29.5%; $n = 13$). The mean elevation of proglacial bedrock-dammed lakes is 260 m higher than the mean elevation of proglacial moraine-dammed lakes, a fact that provides evidence of the evolution of moraine-dammed lakes in the initial phase of glacier retreat (see Section 3.2) and evolution of bedrock-dammed lakes in later phases of glacier retreat as a function of morphological conditions around retreating glaciers. The potential for the formation of large landslide-dammed lake is a possible scenario in any elevational zone, but is more likely at an elevation of below 4500 m a.s.l. Such high-volume slope movements in the Cordillera Blanca may be triggered by a strong earthquake (Cluff, 1971), permafrost degradation (Haeberli, 2013; Haeberli et al., 2016), a strong El Niño cycle (e.g., Vilímek et al., 2014b), or a combination thereof. High-volume slope movements into the lake may also produce displacement waves (e.g., Haeberli et al., 2016; Klimeš et al., 2016) and cause far-reaching process chains such as floods/debris flows (e.g., the process chain in the Santa Cruz valley in 2012; Emmer et al., 2014).

### 4.3. Implications for lake outburst flood hazard management

From the analysis of past lake outbursts in the Cordillera Blanca (see Section 4.1) it seems that young (and often proglacial) bedrock-dammed lakes currently represent the main threat (i.e., they are exposed to the most frequent GLOF triggers – calving glaciers and different types of slope movements), regardless of their size, which rarely exceeds 100,000 $m^2$. On the other hand, in terms of large lakes, moraine-dammed lakes were assessed to be the most susceptible to outburst floods (see Section 3.3). Therefore, we recommend continuous monitoring (e.g., Cochachin et al., 2010; Cochachin and Torres, 2011; UGRH, 2014, 2015) and regular re-assessment of the susceptibility (e.g., Emmer and Vilímek, 2014) of young proglacial bedrock-dammed lakes and large moraine-dammed lakes considering potential future changes and modelling of potential lake outburst flood scenarios (Westoby et al., 2014; Worni et al., 2014; Mergili et al., 2015; Westoby et al., 2015; Somos-Valenzuela et al., 2016).

### 4.4. Methods, data, results interpretation and potential sources of errors

Overall, 882 lakes were manually detected using RS images (with the date of acquisition being 2013 or earlier) and characterised by several qualitative as well as quantitative characteristics. Classification of certain qualitative parameters (such as dam type) is based entirely on a so-called 'expert assessment'. To preserve consistency of the results, all of the lakes were detected and characterised by only one person, using subjective but uniform criteria. Both qualitative as well as quantitative characteristics were checked in the field during repeated field surveys and were also checked with data provided within ANA reports (e.g., Cochachin et al., 2010; Cochachin and Torres, 2011; UGRH, 2014, 2015). Lake level elevations were obtained from various sources, with a preference being given to Alpenverein maps (Alpenvereinskarte, 2005, Alpenvereinskarte, 2006) and ANA reports. Obviously, the less reliable source was the DEM available on Google Earth Digital Globe PRO. Despite the fact that the deviation from reality may be relatively high ($\pm$ tens of meters) for this data source in extreme cases, the overall statistics presented in Section 3.1.2 and Table 5 should not be influenced significantly (bidirectional deviation). The quality of DEMs is also related especially to the estimation of mean slopes of moraines facing the lakes used in the susceptibility assessment; however, for the majority of the large lakes these data were gained from ANA reports (e.g., Cochachin et al., 2010; Cochachin and Torres, 2011; UGRH 2014, 2015) and field surveys and are therefore considered to be reliable.

Remotely sensed data and the corresponding (partly simplified) approach (Emmer and Vilímek, 2014) were used to assess the susceptibility of a high number of lakes to outburst floods (first-order susceptibility assessment). It is important to stress that the methodological approach used does not consider the magnitude of potential triggers (e.g., slope movements) and therefore also disregards the magnitude of potential flood nor downstream impacts – a fact which needs to be taken into account in the interpretation of the results obtained. Moreover, the spatio-temporal occurrence of triggering events is a subject of so called 'quasi-randomness' (O′Connor et al., 2001) limiting the reliability of the results regardless the methodological approach used (for more details on this issue see Emmer and Vilímek, 2014).

## 5. Conclusions

High mountain lakes of the Cordillera Blanca were inventoried and described by a number of quantitative and qualitative characteristics. The subsequent analysis showed relations between different lake types and their characteristics in space and time. It was shown that the number and characteristics of high mountain lakes sensitively reflect ongoing environmental change. Temporal analysis revealed the fact that the majority of glacial lakes whose catchments were already deglaciated in 1948 have persisted without any areal shrinkage to date. It was also shown that the occurrence of lake outburst floods is characteristic for specific periods in lake evolution (proglacial phase) and specific lake types over time. The susceptibility of all large lakes ($n = 64$) to outburst floods was assessed, revealing especially rapid slope movements as a potential trigger of lake outburst floods. The complex monitoring of young proglacial bedrock-dammed lakes and large moraine-dammed lakes focusing on potential triggers of lake outbursts, systematic hazard re-assessment considering potential future changes and flood modelling are all recommended in order to anticipate hazardous situations and processes on time.

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Map. KML file containing the Google map of the most important areas described in this article.

## Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version, at doi: http://dx.doi.org/10.1016/j.catena.2016.07.032.

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