



Research Article

160 glacial lake outburst floods (GLOFs) across the Tropical Andes since the Little Ice Age



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ABSTRACT

Assessing the extent to which glacial lake outburst floods (GLOFs) are increasing in frequency in modern times and whether their incidence is driven by anthropogenic climate change requires historical context. However, progress on this issue is hampered by incomplete GLOF inventories, especially in remote mountain regions. Here, we exploit high-resolution, multi-temporal satellite and aerial imagery, and documentary data to identify GLOF events across the glacierized Cordilleras of Peru and Bolivia, using a set of diagnostic geomorphic features. A total of 160 GLOFs from 151 individual sites are characterised and analysed, tripling the number of previously reported events. We provide statistics on location, magnitude, timing and characteristics of these events with implications for regional GLOF hazard identification and assessment. Furthermore, we describe several cases in detail and document a wide range of process chains associated with Andean GLOFs.

1. Introduction

Glacial lake outburst floods (GLOFs) – sudden releases of water from glacial lakes – are among the most rapid and powerful geomorphic agents in deglaciating mountain regions, with released volumes and peak discharges far exceeding those from other types of flooding (Costa and Schuster, 1988; Evans and Clague, 1994; Carrivick and Tweed, 2016; Cook et al., 2018). The warming of the mountain cryosphere raises concerns about whether associated hazards (Huss et al., 2017;

Immerzeel et al., 2020; Ding et al., 2021), and GLOFs in particular, might become more frequent and/or more severe, and hence of increasing concern to downstream communities and infrastructure (Clague et al., 2012; Haerberli et al., 2016; Vuille et al., 2018; Veh et al., 2020; Stuart-Smith et al., 2021). However, some recent studies have demonstrated a decrease or stagnation in the frequency of such events in some parts of the world over recent decades (Carrivick and Tweed, 2016; Harrison et al., 2018; Veh et al., 2020), highlighting the complexity of understanding GLOF risk in these rapidly evolving

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landscapes. GLOF inventories are particularly helpful in addressing questions surrounding the frequency and magnitude of these events within modern timescales (here referring to the post-Little Ice Age period), and in understanding the possible driving role of anthropogenic climate change and GLOF characteristics for enhanced hazard assessment (e.g. Harrison et al., 2018; Veh et al., 2019). However, in many regions detailed inventories of GLOF occurrence are lacking.

Existing GLOF inventories have either been focussed on a specific region or have been compiled for a global perspective. Regional GLOF inventories are typically derived from documentary data, grey literature, analysis of satellite images, field surveys, or a combination thereof (e.g. Hewitt, 1982; Clague and Evans, 2000; O'Connor et al., 2001; Emmer, 2017). In comparison, global GLOF inventories are commonly based on the compilation of existing regional GLOF inventories, without necessarily attempting to augment these datasets with additional previously unreported events (e.g. Vilfimek et al., 2014; Emmer et al., 2016; Carrivick and Tweed, 2016; Harrison et al., 2018). While global inventories are valuable for deriving a broad appreciation of GLOF spatio-temporal dynamics, detailed studies focussed on a specific region (mountain range, country), which incorporate cross-checking against geomorphological evidence for past GLOFs, typically reveal missing data (Anaconda et al., 2015; Emmer, 2017; Veh et al., 2019; Zheng et al., 2021).

There have been numerous documented GLOFs in the Peruvian Andes, resulting in substantial loss of life and damage to infrastructure (e.g. Lliboutry et al., 1977; Carey, 2005; Carrivick and Tweed, 2016), and to a lesser extent in the Bolivian Andes (Cook et al., 2016; Kougkoulos et al., 2018a, 2018b). There is a long tradition of research on GLOFs in this region, with the Peruvian Cordillera Blanca in particular being one of the most intensively studied regions globally, with respect to GLOF research and hazard mitigation (e.g. Oppenheim, 1946; Lliboutry et al., 1977; Portocarrero, 1984; Zapata, 2002; Reynolds Geosciences Ltd, 2003; Carey, 2005; Portocarrero, 2014; Emmer et al., 2018; Carey et al., 2021). Nonetheless, a unified, national GLOF inventory does not exist for Peru, nor for Bolivia.

To bridge this gap, we aim to generate a GLOF inventory for Peru and Bolivia that integrates available literature and documentary data on observed events, and geomorphological evidence derived from the analysis of remotely sensed imagery and field surveys. Our motivation is the need to understand spatio-temporal patterns of GLOF occurrence and process chains for enhanced GLOF hazard and risk identification, as well as the increasing need of such data to assist with the possible attribution of GLOF events to climate change (e.g. Harrison et al., 2018; Motschmann et al., 2020; Stuart-Smith et al., 2021). Specifically, we seek to assess: (i) the spatial distribution of GLOF events in Peru and Bolivia (Section 4.1); (ii) the characteristics of mapped GLOF events (event types, lake types, GLOF mechanisms, lake-glacier interaction) (Section 4.2); (iii) the timing of GLOF events and the extent to which there is any specific temporal trend in GLOF occurrence as has been found in previous studies (Harrison et al., 2018; Emmer et al., 2020a) (Section 4.3); and (iv) the variety of process chains associated with GLOFs using four detailed case studies (Section 4.4).

2. Study area

This study evaluates GLOF incidence for 20 glacierised Cordilleras in Peru and 5 glacierised Cordilleras in Bolivia (see Fig. 1), and extends from 8.5°S (the northernmost flank of the Cordillera Blanca, Peru) to 17°S (Quimsa Cruz, Bolivia). These extensive and high mountain ranges formed as a result of subduction of the Nazca ocean plate under the South American continental plate, and include peaks up to 6768 m asl (Huascarán Sur, Peru) and 6542 m asl (Sajama, Bolivia). The glaciated Cordilleras of Peru and Bolivia contain about 90% of the world's tropical glaciers (70% in Peru and 20% in Bolivia; Kaser, 1999; Kaser and Osmaston, 2002). However, their areal extent and volume has decreased rapidly since the end of the Little Ice Age (LIA; INAIGEM, 2018), as a

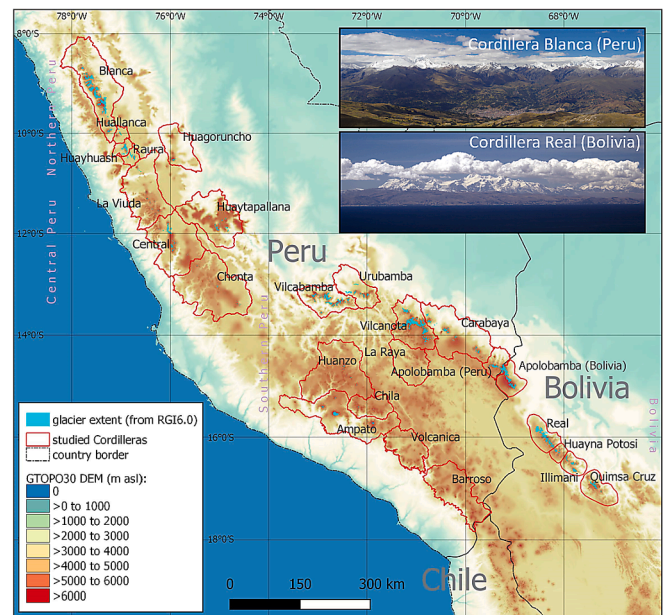


Fig. 1. An overview of the study area - 20 glacierised Cordilleras of Peru and 5 glacierised Cordilleras of Bolivia. Inset images show the west-facing slopes of the Central part of the Cordillera Blanca – the most glaciated and the highest Cordillera of Peru –, and west-facing slopes of the Cordillera Real – the most glaciated Cordillera of Bolivia.

result of historically unprecedented temperature increases (Thompson et al., 2006), estimated to be approx. 0.1 °C per decade in the second half of the 20th Century (Vuille et al., 2008). The effect of this temperature increase outweighs the effect of a slightly increasing precipitation trend in the inner Tropics, and is strengthened by a decreasing precipitation trend in the sub-tropics (Vuille et al., 2008). However, some studies analysing measured data suggest no clear trend in precipitation in at least past five decades (Heidinger et al., 2018; Seiler et al., 2013; Lavado-Casimiro et al., 2013). This translates into negative glacier mass balances (Rabatel et al., 2013; Veettil and Kamp, 2019), which in turn changes the frequency and magnitude of glacial hazards (Haerberli et al., 2016), and the reliability of meltwater supply to people and ecosystems (Huss et al., 2017; Vuille et al., 2018).

Glacier recession and thinning is often accompanied by the formation and evolution of glacial lakes (Buckel et al., 2018; Cook and Quincey, 2015; Wilson et al., 2018; Shugar et al., 2020; Chen et al., 2021); a trend which has been documented in the Peruvian and Bolivian Andes (Iturrizaga, 2014; Cook et al., 2016; Emmer et al., 2020a). Observations from the Cordillera Blanca and three Bolivian Cordilleras reveal that while the overall number of lakes, as well as the total lake area and volume, have been increasing in past decades, the number of proglacial lakes has remained stable or has even decreased recently as a result of glacier retreat beyond locations topographically suitable for the formation of lakes (Cook et al., 2016; Emmer et al., 2020a).

More recently, Wood et al. (2021) presented an inventory of lakes within a 3 km buffer from Peruvian glaciers, revealing a total of 4577 lakes across the country, while the national lake inventory of Autoridad Nacional del Agua (ANA) consists of 2316 lakes (ANA, 2014), and the unpublished inventory of Instituto Nacional de Investigación en Glaciares y Ecosistemas de Montaña (INAIGEM) which also includes lakes located in non glacierized regions consists of 6373 lakes (INAIGEM, 2018). For Bolivia, Cook et al. (2016) found that there were 137 lakes that existed within 0.5 km buffer from mapped ice margins in 2014, although no inventory of lakes has been undertaken since.

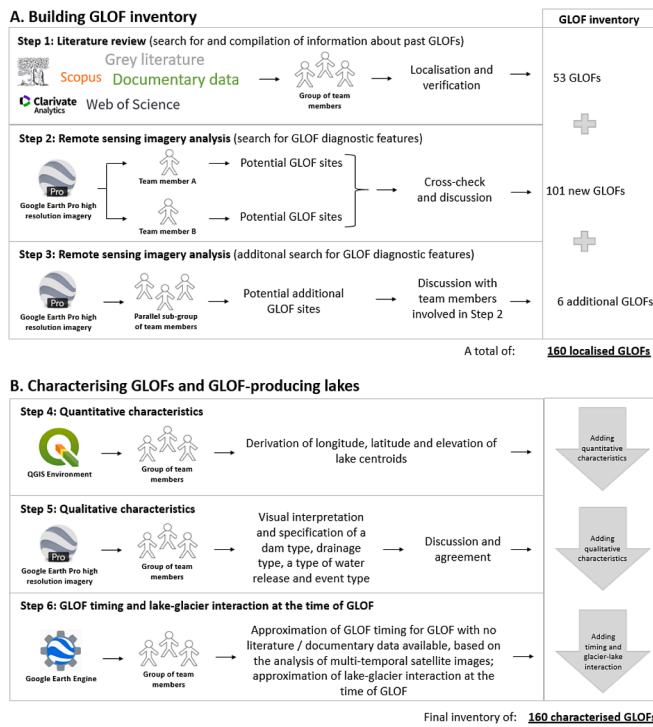


Fig. 2. A flowchart of building GLOF inventory.

Table 1
 Inventoried characteristics.

Characteristic	Description	Value
Lake ID	GLOF-producing lakes were assigned with unique ID; this ID comprises of letter (A, B or C) referring to <i>event type</i> and three-digit number	A total of 160 unique IDs (A_001 to C_120)
Longitude, latitude, elevation	Geographical location (the study includes the glacierized Cordillera of Peru and Bolivia)	67°-78° W 8.5°-17° S 3997 to 5305 m asl
Event type	A magnitude information matrix was designed to classify inventoried GLOFs into three event types	<i>A type event</i> – high magnitude events mentioned in the literature <i>B type event</i> – (high magnitude AND not mentioned in the literature) OR (low magnitude AND mentioned in the literature) <i>C type event</i> – (low magnitude AND not mentioned in the literature)
Mountain range	We searched for GLOF diagnostic features across 20 Peruvian and 5 Bolivian glacierised Cordilleras (Fig. 1)	18 Cordilleras where GLOFs were found
Lake type	Four lake types are distinguished based on the material forming the dam	Moraine-dammed Bedrock-dammed Combined dam Other / not specified
Timing of GLOF	We combined documentary data (previously mentioned GLOFs) and analysis of remote sensing imagery (previously not mentioned GLOFs) to refine the timing of individual GLOF events and the general patterns of occurrence	1725 to 2020
Mechanism of water release	We distinguish between dam failure (characterised by GLOF diagnostic features including breached dam and permanent lake level drawdown) and dam overtopping (characterised by GLOF diagnostic features downstream of the lake with no permanent lake level drawdown)	Dam breach Dam overtopping Not known
Drainage	Two distinct types of drainage are distinguished in this study, reflecting whether the lake persisted after the GLOF or not	Partial lake drainage Complete lake drainage Not known
Lake glacier interaction in the time of GLOF	Three options of lake-glacier interaction were distinguished: (i) proglacial (direct contact between lake and glacier); (ii) glacier detached (no direct contact, but some glaciers in the lake's catchment); (iii) non-glacial (no glaciers in the catchment)	Proglacial Glacier-detached Non-glacial Not known
(likely) trigger	We use available documentary data and/or geomorphic evidence to derive information on (likely) GLOF trigger	<i>Ice-related</i> : calving and ice / ice rock avalanches, ice dam failures <i>Rock-related</i> : landslides, rockfalls and debris flows <i>Water-related</i> : extreme precipitation / snowmelt / flood from upstream <i>Earthquake</i> Not known
Additional information	Additional information about the event	–
References	We provide references to existing studies (where available)	–

3. Data and methods

3.1. General procedure of building the GLOF inventory

The GLOF inventory was built following a six step procedure (see Fig. 2) in which we integrated the review of scientific and grey literature and documentary data sources (Section 3.2), analysis of remotely sensed imagery (Section 3.3), and validation through field surveying (Section 3.4).

1) We reviewed existing literature (including searches in Web of Science and Scopus databases, a grey literature search and a documentary data search; see Section 3.2), returning 53 GLOFs, which we placed into the inventory. 2) We visually explored remote sensing imagery and created a dataset of potential GLOF sites, based on the mapping of GLOF diagnostic features (see Section 3.3 for details). Two mapping campaigns were undertaken independently by two team members, and final GLOF sites included in the inventory consist of agreed sites between the mapping results of these two members. 3) Additional mapping of GLOF diagnostic features was undertaken by a parallel group of team members; this largely confirmed the mapping results from Step 2, although an additional six GLOFs were included at this stage (see Fig. 2). These internal, independent checks yield a robust final inventory.

In the next three steps, we characterised each GLOF site using several quantitative and qualitative characteristics (see Table 1). 4) Quantitative characteristics, including longitude, latitude and elevation of GLOF-producing lakes, were derived automatically in a GIS environment (QGIS, v. 3.10 A Coruña), while 5) qualitative characteristics (dam type,

drainage type, mechanism of water release, event type, lake-glacier interaction at the time of GLOF) were assigned manually based on the visual interpretation of high-resolution remotely sensed imagery (Emmer, 2017; Emmer and Cuřín, 2021). Here, four lake dam types are distinguished (moraine-dammed, bedrock-dammed, combined dams and others), two mechanisms (dam failure or dam overtopping) and two drainage types (partial or complete). Emmer (2017) showed that well-developed GLOF diagnostic features (breached dam, outwash fan(s), decreased lake water level) indicate a high magnitude GLOF. This approach is adopted in the current study using a qualitative assessment of GLOF diagnostic features (high magnitude events with well-developed GLOF diagnostic features, low magnitude events with less-developed (partly missing) GLOF diagnostic features). Additionally, each GLOF event is assessed as to whether it has been previously recognised within the literature (mentioned previously or not), resulting in three event types (A, B, C; see Table 1). Type A refers to a high magnitude event previously mentioned in the literature, while type C refers to low magnitude events not mentioned previously. Type B covers the remaining combinations (high magnitude, not mentioned previously; low magnitude, mentioned previously). Two lake-glacier interactions at the time of the GLOF event are also distinguished (proglacial or glacier-detached).

6) Finally, GLOF timing was established, in many cases, from existing literature and documentary data. For cases where this was not possible, remotely sensed images were employed to establish approximate GLOF timing. Where multiple outbursts have occurred from one lake (e.g. Lake Palcacocha in the *C. Blanca* which produced GLOF in 1941 and 2003; see Vilímek et al., 2005; Huggel et al., 2020), we consider each event separately in the inventory, but maintain the lake ID with “_2” suffix (i.e. event ID A_011 for the 1941 GLOF, and A_011_2 for the 2003 GLOF event from Lake Palcacocha).

3.2. Literature review and the analysis of documentary data

Our literature review analysed scientific literature, grey literature and documentary data (studies and reports not available online, physical copies stored in the archives; see Table 2). We used the ‘Advanced Search’ tool of the Clarivate Analytics Web of Science Core Collection database (WOS, n.d.) and the ‘Advanced Search’ tool of Elsevier’s Scopus database (SCOPUS, n.d.) to search for studies containing information about past GLOFs in Peru and Bolivia. To this end, we used strings combining topical specification (string: (glaci* AND lake* AND

outburst*) OR GLOF* OR jokulhlaup*) with geographical specification (string: Peru* OR Bolivia* OR Andes) of targeted studies. Both databases returned ~80 papers which we manually checked for relevant information. Only a small proportion of the papers contained relevant information about past GLOFs in the region of interest.

Grey literature (i.e. reports published by local institutes in charge of lake research and monitoring [e.g. Autoridad Nacional del Agua; ANA, Instituto Nacional de Investigación en Glaciares y Ecosistemas de Montaña; INAIGEM, and Instituto Geológico, Minero y Metalúrgico; INGEMMET]) represent an important data source for past GLOFs. Online repositories (e.g. ANA’s repository at <http://repositorio.ana.gob.pe>) were also used to build our inventory. However, it is important to mention that research interest varies considerably across individual Cordilleras, which affects the amount of available grey literature and documentary data considerably. Some of the Cordilleras have been the subject of lake and GLOF research by local institutes as well as foreign researchers for decades (e.g. Peruvian *C. Blanca* and *C. Huayhuash*; see Kinzl et al., 1954; Lliboutry et al., 1977), while others - especially less inhabited Cordilleras - have not. Reports and studies describing individual events (e.g. Kinzl, 1940; Broggi, 1942; Oppenheim, 1946; Indacochea and Iberico, 1947; Spann, 1947; Ghiglini and Spann, 1951; Torrés and Brotgger, 1951; Vilímek et al., 2005, 2015; Morales, 1966; Kougkoulos et al., 2018b; Mergili et al., 2018, 2020; Huggel et al., 2020; Vilca et al., 2021) and sub-regional GLOF inventories (e.g. Lliboutry et al., 1977; Portocarrero, 1984; Zapata, 2002; UGRH, 2013; Portocarrero, 2014; Emmer, 2017; Bat’ka et al., 2020; Motschmann et al., 2020) are available in existing scientific and grey literature and documentary data.

Considering these documentary data (i.e. those sources physically stored in archives, and not available online), we analysed available data from the regional office of ANA in Huaraz, Ancash Region, Peru, where various documentary data are stored, including: (i) reports from survey and monitoring campaigns; (ii) detailed maps and technical drawings; (iii) field images. These sources are dated back to the late 1940s and include studies with Peru-wide focus and a large amount of documentary data specifically focusing on past lake and GLOF research activities, mainly in the *C. Blanca* and *C. Huayhuash*. These studies were already exploited by Emmer (2017) for the GLOF inventory of the *C. Blanca* and by Bat’ka et al. (2020) for the GLOF inventory of *C. Huayhuash*. Available documentary data focusing on other Cordilleras are comparably limited. Further, we exploited the INGEMMET archive in Lima.

3.3. Remotely sensed images and mapping GLOF diagnostic features

We exploited remotely sensed images and derived products of various origins, spatial resolution and time span (see Table 3). While the whole study area is covered by satellite images from the late 1970s / early 1980s (Landsat images), historical aerial images allowed more detailed analysis in specific parts of the study area (*C. Blanca*, going back to 1948; Emmer, 2017). We used Google Earth Engine to access repeat-pass satellite imagery (Landsat 2, Landsat 5, Landsat 8, Sentinel 2) in order to evaluate GLOF timing. PlanetLabs (<https://www.planet.com/>) was also used to determine the timing of more recent (mostly since ~2016) GLOF events. For both platforms, this was achieved iteratively by progressively narrowing the time window in our search terms to look for the absence (pre-GLOF) and presence (post-GLOF) of diagnostic geomorphological features. Our literature search revealed precise timings for a number of events, but many GLOFs in our inventory are previously unknown. Analysis of satellite data allowed us, in many of these cases, to identify GLOF timing to within a closed window of time (often to within a few months or one calendar year). In several instances, however, we were only able to describe an open time window (i.e. before a specific date). We also used freely available digital elevation models (DEMs) in evaluating geomorphological evidence for GLOFs, and for visualisations and analysis; GTOPO30 for large-scale visualisations and analysis (~1 km resolution), SRTM for more detailed visualisations and

Table 2
Literature sources used for review of documented GLOFs.

	Description	Source	Examples
Scientific literature	Studies published by research community (journal papers and books)	Web of science (WOS, n.d) SCOPUS database (SCOPUS, n.d.)	Mergili et al. (2020); Vilca et al. (2021)
Grey literature	Studies and reports published by governmental institutes, available online	Autoridad Nacional del Agua online repository (ANA, n. d) Instituto Nacional de Investigación en Glaciares y Ecosistemas de Montaña webpage (INAIGEM, n.d.)	INGEMMET (2010); Reynolds Geo-sciences (2003); INAIGEM (2018); Vilca (2019)
Documentary data	Studies and reports not available online, physical copies stored in the archives	ANA archive in Huaraz INGEMMET archive in Lima	Oppenheim (1946); Indacochea and Iberico (1947); Spann (1947); Torrés and Brotgger (1951)

Table 3
Remotely sensed data and derived products used in this study.

Data	Time span / acquisition date	Area coverage	Spatial resolution	Availability
Remotely sensed images:				
Landsat images	From late 1970s to present	Whole study area	60/30/15 m	USGS LandsatLook (LandsatLook, n.d.); Google Earth Engine (GEE, n.d.)
Sentinel 1 and 2 images	From 2014 to present	Whole study area	5 to 60 m	Sentinel Hub EO Browser sentinel (EO browser, n.d.)
CNES / Airbus / Google / Maxar Technologies	From 2000s to present	Whole study area	Submetrical to 2–3 m	Google Earth Digital Globe (GEDG, n.d.)
PlanetLabs images	2016 to 2020	Whole study area	3 to 5 m	Planet Labs Inc. (Planet, n.d.)
Aerial images	Three sets (1948, 1962, 1970)	Cordillera Blanca	3 m	ANA archive in Huaraz
Digital elevation models (DEMs)				
GLOBTOPO30	1996	Whole study area	30 arcsec (approx. 1 km)	USGS Earth Explorer (EarthExplorer, n.d.)
SRTM	2000	Whole study area	30 m	USGS Earth Explorer (EarthExplorer, n.d.)
Glacier inventory:				
Randolph glacier inventory (RGI)	Based on images from 1990 to 2009	Whole study area	Not specified (vector layer)	Global Land and Ice Measurements from Space (RGI Consortium, 2017)

analysis (30 m resolution), and the Google Earth Digital Globe Pro DEM for deriving lake level elevations (largely based on ALOS PALSAR DEM with 12.5 m / 30 m resolution).

Robitaille and Dubois (1995) determined characteristic features of outburst floods, which have been employed in subsequent studies by Emmer (2017) in the Cordillera Blanca and Bat'ka et al. (2020) in the Cordillera Huayhuash. We adopted this set of defined GLOF diagnostic features to look for previously unreported GLOF sites using high resolution imagery available via Google Earth Digital Globe (GEDG, n.d.). These features include: (i) Breached moraine dams; (ii) Outwash fan located downstream from the lake dam (typically formed by material eroded from the dam during the GLOF); (iii) visible lake level drawdown associated with permanent or temporary post-GLOF lake level decrease (excluding seasonal lake level fluctuations). These typical diagnostic features of GLOFs in the study area are shown in Fig. 3. Some of the GLOF diagnostic features may not be present in all cases (e.g. breached dam in the case of GLOFs originating from bedrock-dammed lakes). Decisions about whether observed features are associated with a past GLOF can be a somewhat subjective task. For this reason, the stepped procedure introduced above (see Section 3.1 and Fig. 2) provided several internal, independent checks to ensure the accuracy of the final agreed inventory.

3.4. Field surveying and informal interviews with locals

Starting in the early 2010s, selected sites that have experienced GLOFs were visited by members of the team during repeated field surveys in Peru and Bolivia. Field data used in this study mainly include the reconnaissance of the GLOF sites, photodocumentation and subsequent validation of visual interpretation of remote sensing imagery. This field validation included detailed geomorphological mapping of GLOF diagnostic features and palaeogeographical interpretation of erosional and depositional landforms using laser rangemeters and/or inclinometers Trupulse E200 (see details in Emmer, 2017). Visited GLOF sites are located across the whole studied region, mainly including C. Blanca (extensive field work done between 2012 and 2019), C. Huayhuash (2018 and 2019) and C. Apolobamba (2015).

Some of the field surveys also included informal interviews with locals. For instance, local herders living in the Pampa Shonquil were interviewed by AE after the 2010 GLOF from Lake no. 513, providing valuable insights into the dynamics and evolution of the process chain and erosion-accumulation interactions. These interactions have been analysed in detail by Vilfimek et al. (2015). Also, during a field campaign in the Santa Cruz valley in 2015 focusing on the 2012 GLOF, a mountain

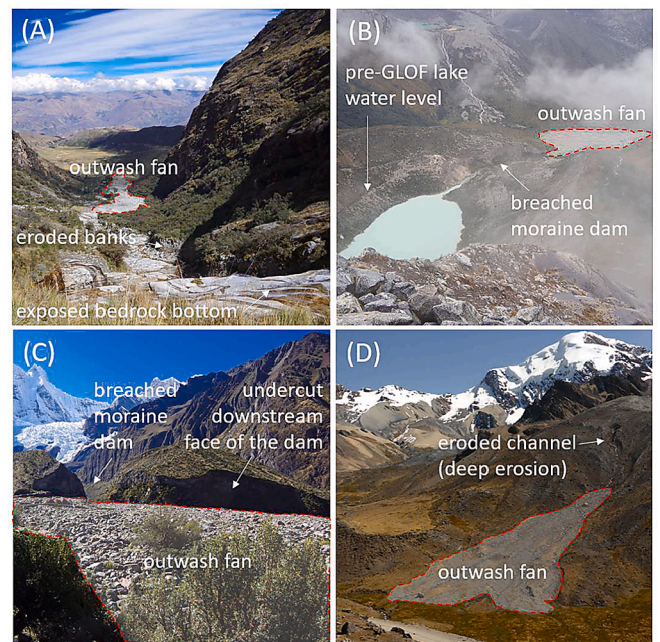


Fig. 3. Examples of selected GLOF sites with highlighted GLOF diagnostic features. (A) shows the downstream view from the bedrock dam of Lake No.513 (Cordillera Blanca, Peru; GLOF site ID B_042); visible GLOF diagnostic features resulting from a GLOF in 2010 (image taken in 2018); (B) shows the downstream view of the moraine-dammed lake Artesoncocha (Cordillera Blanca, Peru; GLOF site ID A_015) which experienced two GLOFs in the 1950s; outwash fan as well as pre-GLOF lake water level are still clearly visible on the image from 2014; (C) shows the upstream view of the deep moraine dam breach of Lake Solteracochoa (Cordillera Huayhuash, Peru; GLOF site ID A_007), which produced a GLOF in 1932 with an outwash fan in the forefield (image taken in 2018); (D) shows the outwash fan of a GLOF (Cordillera Apolobamba, Bolivia; GLOF site ID B_006) (image taken in 2015). Images: Adam Emmer (A-C), Simon Cook (D).

guide confirmed to AE the occurrence of repeated GLOFs in the valley (in 1997 and 2012; see Mergili et al., 2018). One of us (SJC) travelled to C. Apolobamba in 2015 and discussed GLOF incidence there. Whilst a village leader recounted a story of his father witnessing a GLOF, no further details were available about precise location, timing or magnitude of the event. Unfortunately, this secondhand information was too

sparse to be included in any meaningful way, but does at least testify to the fact that GLOF events have hitherto been underreported in this region. Indeed, interviews with locals can provide valuable information about the timing, magnitude, evolution, course and societal impacts of these events (Watanabe et al., 2016; Byers et al., 2020; Carey et al., 2021), however, no systematic interviews were conducted for this particular study and information gained from locals are rather complementary to our other, more systematic analyses.

4. Results

4.1. Spatial GLOF distribution

Our inventory contains a total of 160 GLOFs occurring from 151 individual lake sites across Peruvian (139 GLOFs from 131 lakes) and Bolivian Andes (21 GLOFs from 20 lakes; see Fig. 4). Information about and geomorphic evidence of past GLOFs were found in 16 Cordilleras (11 located in Peru, 4 in Bolivia and 1 cross-border (C. Apolobamba); see Table 4). The majority of GLOFs were inventoried in C. Blanca ($n = 60$; 37.5% of all), followed by C. Vilcabamba ($n = 21$; 13.1%), C. Apolobamba ($n = 16$; 10.0%, of which 11 were in Bolivia and 5 in Peru), C. Huayhuash ($n = 14$; 8.8%) and C. Vilcanota ($n = 12$; 7.5%). The remaining 37 GLOFs (22.6%) are found in C. Urubamba ($n = 10$), C. Huaytapallana ($n = 6$), C. Real ($n = 6$), C. Central ($n = 4$), C. La Viuda ($n = 3$), C. Quimsa Cruz, C. Huallanca ($n = 2$ each), C. Carabaya, C. Chonta, C. Illimani and C. Huayna Potosi ($n = 1$ each). No information about nor evidence of past GLOFs were found in C. Ampato, C. Barroso, C. Chila, C. Huagoruncho, C. Huanzo, C. Raura, C. La Raya or C. Volcanica. Three apparent hotspots of spatial GLOF concentration are visible from the heatmap (Fig. 4), these being located in the C. Blanca (most prominent) hotspot and less prominent C. Vilcabamba – C. Urubamba and C. Apolobamba hotspots. Altogether these hotspots account for 107 (66.9%) of the GLOFs in the inventory.

GLOF-producing lakes are located in elevations ranging from 3997 to 5305 m asl, with median elevation of 4640 m asl (interquartile range of 4455 to 4855 m asl; see Fig. 5). We found that differences exist between parts (spatial clusters) of the study area, with highest elevations of GLOF-producing lakes observed in the southernmost part (C. Apolobamba and Cordilleras of Bolivia; interquartile elevational range of

Table 4

Number of inventoried GLOFs, lakes and total lake area in individual Cordilleras, countries and throughout the study area. Bold values used to highlight sub-totals for individual countries (Peru, Bolivia) and the total.

Cordillera	No. of inventoried GLOFs	No. of lakes ^a	GLOFs-per-lake-count ratio	Total lake area [km ²] ^a	GLOFs per lake area [km ⁻²]
Blanca	60	803	0.0747	38.72	1.5496
Huallanca	2	69	0.0290	1.68	1.1905
Huagoruncho	0	145	0	12.33	0
Huayhuash	14	129	0.1085	6.92	2.0231
Raura	0	245	0	16.36	0
La Viuda	3	442	0.0068	46.56	0.0644
Huaytapallana	6	373	0.0161	18.77	0.3197
Central	4	509	0.0079	37.92	0.1055
Chonta	1	212	0.0047	11.06	0.0904
Urubamba	10	139	0.0719	3.32	3.0120
Vilcabamba	21	183	0.1148	4.81	4.3659
Vilcanota	12	490	0.0245	49.33	0.2433
Carabaya	1	590	0.0017	46.86	0.0213
Apolobamba (P)	5	142	0.0352	30.88	0.1619
Huanzo	0	54	0	1.64	0
Chila	0	13	0	0.97	0
Ampato	0	19	0	0.73	0
Sub-total (Peru):	139	4557	0.0305	328.86	0.4227
Apolobamba (B)	11	203	0.0542	26.24	0.4192
Real	6	175	0.0343	17.43	0.3442
Huayna Potosi	1	81	0.0123	7.57	0.1321
Illimani	1	68	0.0147	3.54	0.2825
Quimsa Cruz	2	125	0.0160	17.42	0.1148
Sub-total (Bolivia)	21	652	0.0322	64.25	0.3268
TOTAL	160	5209	0.0307	393.11	0.4070

^a Counts and areas of lakes in Peruvian Cordilleras are derived from Wood et al. (2021), counts and areas of lakes in Bolivian Cordilleras are derived from Cook et al. (2016).

GLOF-producing lakes here is 4840–5056 m asl), while the lowest lakes are found in northern Peru (C. Blanca, C. Huayhuash) interquartile elevational range of GLOF-producing lakes is from 4363 to 4664 m asl). Furthermore, we observed different elevations of GLOF-producing lakes depending on the lake dam types, revealing the highest interquartile elevational range for bedrock-dammed (4667–5036 m asl) and the lowest interquartile elevational range for moraine-dammed GLOF-producing lakes (4368–4680 m asl).

We related GLOFs to the total lake count and area (Wood et al., 2021; Cook et al., 2016), revealing that a GLOFs-per-lake-count ratio throughout the study area is 0.0307 GLOFs per lake (0.0339 if Cordilleras with no GLOFs are excluded). This number simply means that on average 3 lakes from a hundred lakes produce a GLOF. However, this ratio varies by two orders of magnitude among individual Cordilleras with GLOFs: from 0.0017 (C. Chonta) to 0.1148 (C. Vilcabamba; see Table 4). The highest GLOFs per lake area is observed in C. Vilcabamba (4.37 GLOFs per km² of lake area), followed by C. Urubamba (3.01 GLOFs per km² of lake area), and C. Huayhuash (2.02 GLOFs per km² of lake area). Throughout the study area, 0.41 GLOFs per km² of lake area are documented.

4.2. GLOF characterisation

A total of 24 GLOFs (15.0%) were classified as A-type events (high magnitude and mentioned in the literature), 47 GLOFs (29.4%) as B-type events (low magnitude and mentioned in the literature, or high magnitude and not mentioned in the literature) and the remaining 89 GLOFs (55.6%) as C-type events (low magnitude, not mentioned previously in the literature). Half of the A-type GLOFs occurred in the C. Blanca ($n = 12$), where most GLOFs are inventoried and where

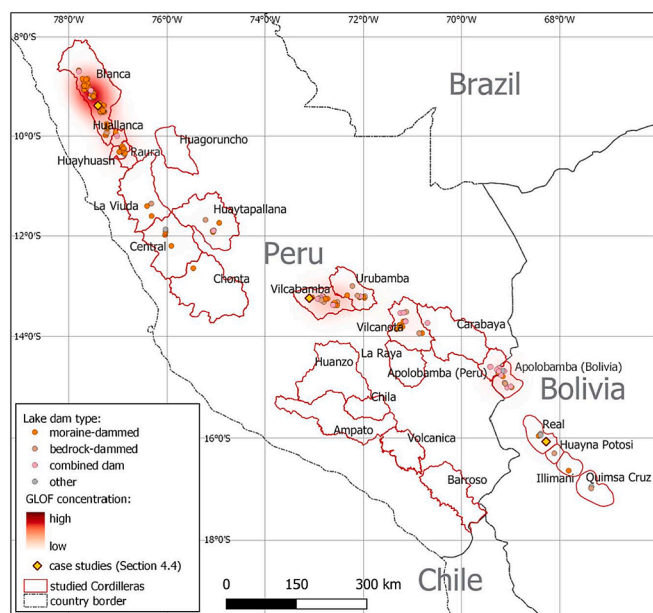


Fig. 4. Location of inventoried GLOFs, spatial GLOF concentration heatmap and lake dam types. Three GLOFs described in detail in Section 4.4 are highlighted.

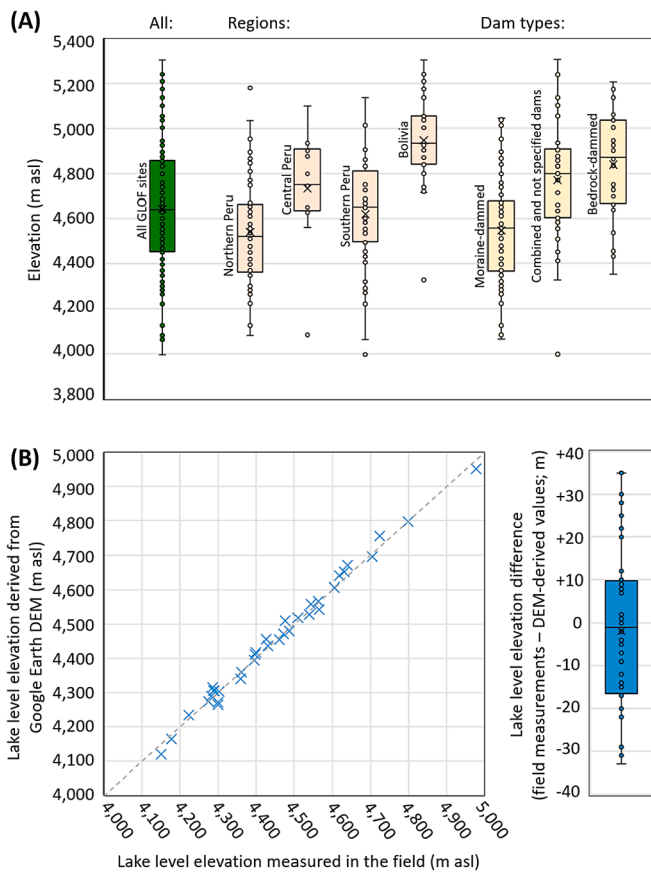


Fig. 5. Elevations of GLOF-producing lakes. (A) shows lake level elevation of GLOF-producing lakes in 4 spatial clusters (see Fig. 1) and among 3 lake dam types (boxplot shows Q1, median, mean (x) and Q3; values within Q1–1.5*IQR (inter-quartile range) and Q3 + 1.5*IQR and outliers). (B) shows a comparison of Google Earth Pro DEM with field measurements of 35 lakes of the Cordillera Blanca (data from Muñoz et al., 2020); interquartile range of differences between measured and DEM-derived elevations is +9 / -17 m, and the maximum differences are +35 / -33 m.

available documentary data and old aerial images allowed the most detailed insights (Emmer, 2017). The source of 99 GLOFs (61.9%) were from moraine-dammed lakes, 29 GLOFs (18.1%) originated from lakes with combined dams (bedrock with discontinuous moraine cover), 26 GLOFs (16.3%) from bedrock-dammed lakes and the remaining 6 GLOFs (3.8%) from other lake types (including ice-dammed lakes and other lake types; see Fig. 6). In terms of GLOF mechanisms, dam overtoppings account for 71 cases (44.4%) while dam breaches (failures) for 68 cases (42.5%). The mechanism of the remaining 21 GLOFs (13.1%) is not clearly identifiable or is classified as 'other' (e.g. the mechanism of the GLOF from Lake Safuna Alta in 1970 is piping; Hubbard et al., 2005).

The lake-glacier interaction at the time of the GLOF is known in 112 cases (70.0% of all); of which 76 GLOFs occurred from proglacial lakes and 36 GLOFs from lakes in the glacier-detached phase of evolution (no direct contact, but some glaciers in the catchment). No GLOF occurred from the lake located in deglaciated catchment. A total of 15 GLOFs (9.4%) resulted in complete lake drainage, whilst the lake persisted after the GLOF (in reduced or original size) in 144 cases (90.0%). In some specific cases, the lake refilled after complete drainage (see Section 4.4.1). A total of 10 out of these complete lake drainages (66.6%) are classified as high magnitude GLOFs, corroborating higher magnitude of GLOFs associated with higher volumes involved / complete lake drainages. High magnitude (A-type) GLOFs were frequently associated with failures of moraine dams ($n = 19$; 79.2%). Only 22C-type events (24.7% of all C-type events) were associated with dam breaches while the

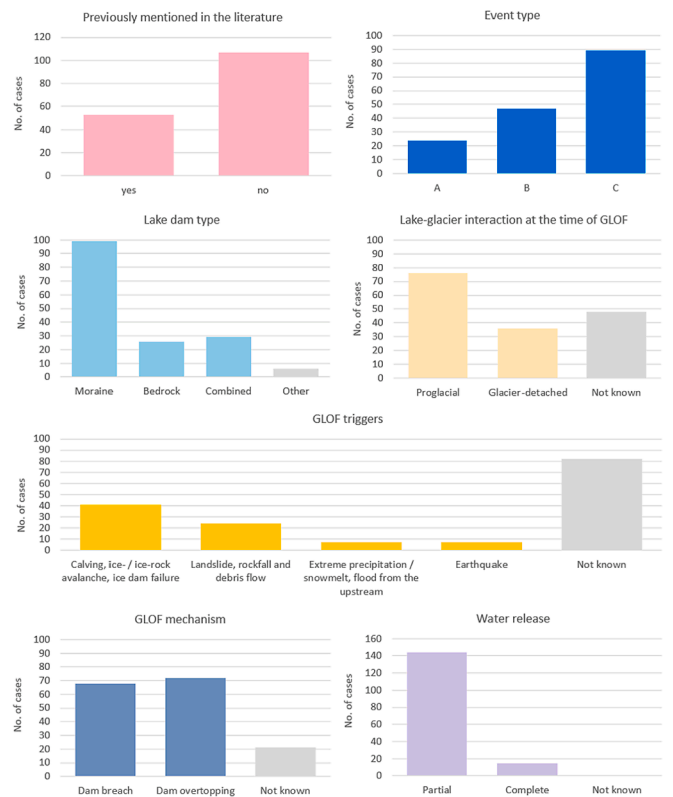


Fig. 6. An overview of basic characteristics of GLOFs in the dataset. *for definition of event types see the main text (Section 3.1) and Table 1.

majority of 75.3% were associated with dam overtoppings (see Fig. 6).

Triggers (including likely triggers) are known for 78 GLOFs in the inventory (48.8%); these were primarily derived from existing literature and documentary data sources, with the remaining GLOF triggers deduced, where possible, from analysis of remote sensing images and geomorphic evidence. Our analysis shows that various ice-related triggers (e.g. ice-/ ice-rock avalanche, ice dam failure) are the most frequently observed GLOF triggers in the Tropical Andes ($n = 41$; 52.6% of cases with known trigger; 25.6% of all), followed by landslide triggering (including landslide, rockfalls and debris flows into the lake), corroborating previous findings of Lliboutry et al. (1977), Portocarrero (1984), Zapata (2002) and Emmer and Cochachin (2013). Several studies elaborate on these GLOF triggering mass movements (e.g. Hubbard et al. (2005) and Klimeš et al. (2021) for the Zapata, 2002 GLOF from lake Safuna Alta; Schaub et al. (2016) for the 2010 GLOF from lake No.513, and Vilca et al. (2021) for the 2020 Salkantaycocha GLOF). Finally, earthquakes and extreme rainfalls were also documented (or at least speculated) to have triggered a number of the GLOFs in the inventory (see Fig. 6).

4.3. GLOF timing

Time-series analysis of GLOF events with known or well-constrained (i.e. to within 1 year) dates ($n = 70$, i.e. 43.75%) indicates that there has been an apparent overall increase in GLOF incidence from 1725 (the first dated event in the inventory) to the present day, although with substantial year-on-year variation, including several years without GLOFs (see Fig. 7A). There are notable maxima in 1970 and in 2019, where 6 and 5 GLOFs, respectively, were recorded. Several years in the post-2020 period experienced as many as 4 GLOFs, and most years since 2000 have recorded one or more GLOFs. While the early part of the record (1725–1970) is dominated by moraine dam failures - many of which were high magnitude (Type A / B) - GLOFs have been initiated

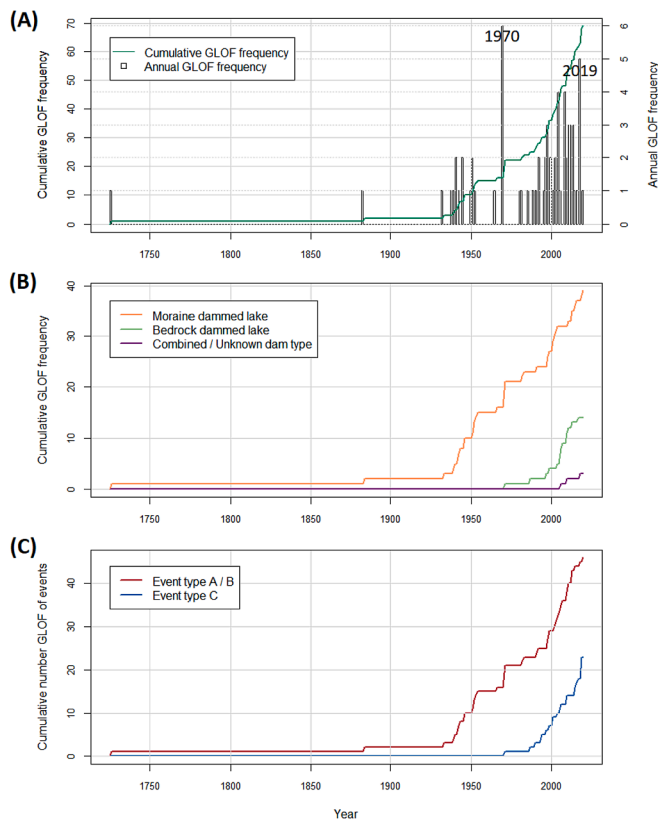


Fig. 7. The occurrence of GLOFs over time. (A) shows cumulative and annual GLOF frequency for all GLOF events with known date or those within a one year time window of occurrence; (B) shows cumulative annual GLOF frequency by dam type, and (C) by event type.

from a mixture of moraine-dammed, bedrock-dammed and combined-dammed lakes since 1970 (see Fig. 7B). There is also an increase in type-C events from 1970, indicating that low magnitude events have become more common, more frequently documented or are now identifiable through available satellite imagery (Fig. 7C; see Section 5.1).

The GLOF frequency maximum in 1970 is apparently related to a large earthquake striking the Cordillera Blanca on 31st May, resulting in 6 minor to moderate GLOFs, but surprisingly no major one (Lliboutry et al., 1977; Emmer, 2017). In more recent years, there have been 4 or 5 GLOFs in a single year (2005, 2009, 2018), although the underlying cause is less clear. On the one hand, there is an apparent increase in GLOF frequency since the 1980s, albeit with interannual variations and some years with no GLOFs (Fig. 7A).

The source of GLOF events has evolved over the study period. Before 1970, all recorded GLOF events were from moraine-dammed lakes; since 1970, GLOFs have been generated from moraine-dammed, bedrock-dammed and combined-dammed lakes (Fig. 7B). One possible explanation for this is that glaciers have now receded far from their Little Ice Age maximum moraines, and many of the lakes that would have formed and been dammed by such moraines either remain stable, have burst already, reduced in size due to decreased connectivity with glacier meltwater systems, or are now less susceptible to failure at an increased distance from glacier-related GLOF trigger mechanisms (such as calving and ice avalanches; Cook et al., 2016; Emmer et al., 2020a). Additionally, there may be an increased propensity for GLOFs from bedrock-dammed lakes because many glaciers have now receded to higher-altitude erosional basins, carved into the bedrock (e.g. Wood et al., 2021), which, by proximity to glaciers and recently deglaciated unstable steep slopes, become more susceptible to glacier-related GLOF triggers. Fewer GLOFs from bedrock-dammed lakes in the pre-1970 period can also be associated with the longevity of diagnostic features of these

GLOFs, and hampered by a lack of available satellite imagery (see also Section 5.1). However, one of our case studies documents the persistence of GLOF diagnostic features for a small-magnitude GLOF originating from bedrock-dammed lake (of ~15 years) (see Section 4.4.2).

4.4. Case studies

Selected GLOFs events, illustrating a variety of process chains, are described in this section. These GLOFs have not previously been documented in detail.

4.4.1. Ice and rock avalanche-induced complete lake drainage and subsequent reappearance

The first GLOF to be discussed in detail occurred in the western part of the Cordillera Vilcabamba, directly at the base of the Panta (Chachacumayoc) peak (5667 m asl). This GLOF is notable as it was observed that the lake has disappeared completely as a result of a drainage event, before later reappearing. Located at an elevation of approx. 4450 m asl, the disappearance of the 9550 m² lake was most likely associated with an ice and rock avalanche, originating from the west-facing slope of the Panta peak, clad in a heavily crevassed hanging glacier. Fig. 8A shows oblique GoogleEarth® views at different points in time, whereas Fig. 8D hypothesizes on the key mechanisms governing the process chain. Time of occurrence can be constrained to the 2012/2013 rainy season, between 11th September 2012 and 25th May 2013 (no cloud-free imagery could be obtained for the time period in between). The exact origin of the ice avalanche cannot be conclusively derived from the available imagery due to the generally high dynamics of the glacier. However, the main candidate for this is a scarp which is located near the summit of the Panta peak, at approx. 5450 m asl (Fig. 8A). Located beneath steep slopes, the lake was drained completely by the avalanche impact, and its basin was subsequently buried with ice and rock. The avalanche itself stopped approx. 400 m farther downstream from the lake.

Both the appearance of the most likely avalanche release area and the estimated volume of the deposited mass (in the order of 10⁵ m³) reveal ice as the main phase, with some subordinate content of rock and debris, some of which possibly originates from entrainment in the lower portion of the slope. The distal approx. 500 m of the observed runout zone is attributed to the drained lake water (possibly containing some ice and debris), as there are few significant deposits of solid material visible in the imagery. The lateral extent of the flooding is clearly visible (Fig. 8B); it shows a rather gradual transition to the floodplain downstream, without a clear terminus. The lake was presumably rather shallow, as otherwise a more far-reaching flood would have been expected downstream.

This case represents a rare example of complete lake drainage associated with a large ice- / ice and rock avalanche. As a direct consequence of material deposition in the main valley, a new landslide-dammed lake formed and had reached a maximum area of 10,000 m² by 2020. The original lake, which had drained completely during the GLOF event, started to re-appear subsequently (Fig. 8C), likely as a result of melting of the ice incorporated within the avalanche deposits. The re-appeared lake had an area of 5780 m² in 2020 (60.5% of the original lake size).

4.4.2. Low magnitude GLOF attenuated in downstream located lake

Our second case study describes the evolution of the upper part of the Ishinca valley in the central Cordillera Blanca, which experienced rapid post-LIA glacier retreat, resulting in the formation of glacial lakes in the main valley as well as in the tributary valleys. The LIA moraine-dammed lake Milluacocho located in the main valley produced two GLOFs in the past (dam breach-associated GLOF in 1952 and dam overtopping-associated GLOF in 1982; Concha, 1953; Emmer, 2017). Continuing glacier retreat, to elevations above 5000 m asl, led to the formation and evolution of a generation of bedrock-dammed lakes (see Emmer et al.,

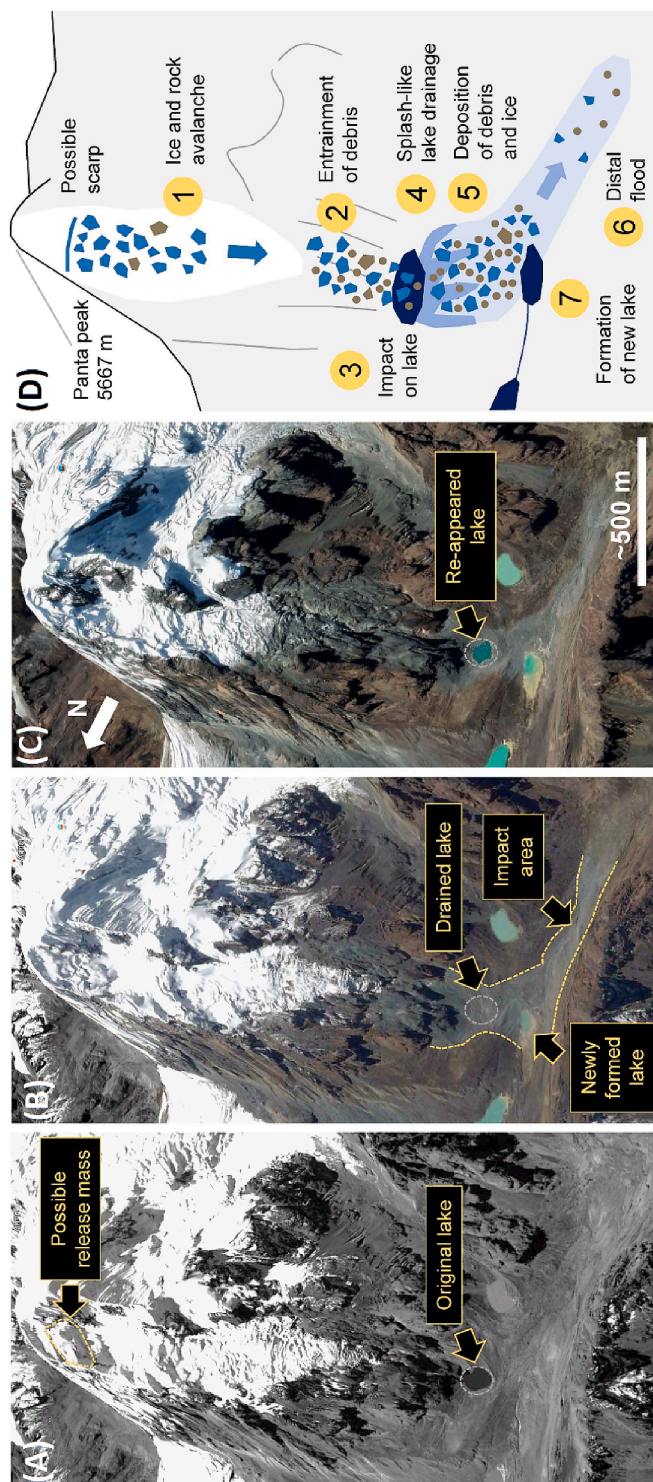


Fig. 8. An example of the GLOF process chain at Panta peak (for location see Fig. 4). (A) shows annotated oblique views of the pre-event situation (Google Earth CNES / Airbus image from 8th August 2012); (B) shows the post-event situation (Google Earth Maxar Technologies / CNES / Airbus from 16th August 2014); and (C) shows the situation after the reappearance of the drained lake (Google Earth Maxar Technologies from 28th May 2020). (D) illustrates the key mechanisms most likely governing the process chain (excluding the reappearance of the drained lake).

2020a). One of these – Unnamed lake (5179 m asl) located on the NE-facing slopes of the Ishinca massif (5530 m asl; see Fig. 9A) – produced GLOF between 4th April and 3rd July 2005.

Analysis of multitemporal remote sensing imagery reveals that the lake started to form in the early 2000s. Fine-grained lacustrine sediments found in the current lakeshore area indicate that the lake level was higher in the past, implying that the lake was ice-dammed at least for some period of its evolution. However, the question of whether the 2005 GLOF occurred as a result of the failure of this temporarily icy part of the dam, or whether it was associated with overtopping of the bedrock part of the dam, remains unanswered. A possible trigger for a dam-overtopping induced GLOF would be a calving event from the steep ice walls facing the lake (Fig. 9D). The 2005 GLOF-affected a total area of 45,800 m² (23,100 m² affected by erosion and 22,700 m² covered by deposition; see Fig. 9B,C) with a clearly distinguishable erosion section (steeper parts) and (gently-sloped) accumulation section. Our field observations revealed that this low magnitude event mobilised boulders up to 0.4 m in diameter. Most of these boulders were deposited in the pampa-like plateau, behind the outer slope of the LIA moraine, in the main valley (see Fig. 9C). The liquid phase of the GLOF likely travelled farther downstream, where it crossed the LIA moraine ridge and eroded its inner slopes where the profile gets steeper. The flood waters then entered lake Toclla, situated in the main valley. No geomorphic evidence of this event is documented further downstream, implying that this low-magnitude GLOF was attenuated in lake Toclla.

This low magnitude GLOF process chain documents some important considerations: (i) there was a shift of GLOF source from moraine- to bedrock-dammed lake through time (second generation lakes formed as glaciers retreated back into depressions carved in the bedrock); (ii) the GLOF diagnostic features of low magnitude events have longevity, being clearly visible in recent satellite images, i.e. 15 years after the event (see also Section 4.2); (iii) downstream lakes can play an important role by attenuating GLOF events by inhibiting the propagation of the process chain further downstream.

4.4.3. Rainfall- / snowmelt-triggered low magnitude GLOF

Our third case study documents a low magnitude GLOF originating from a small unnamed lake located beneath the Mullu Apachita (5368 m asl) in the C. Real, Bolivia (see Fig. 10). Available high resolution images reveal that this GLOF occurred between June 2010 and July 2015. At the time of the GLOF, the lake was located far away from retreating glaciers (> 500 m) and there is no geomorphic evidence of any slope movement entering the lake. Based on these indices, we hypothesize that this event may have been triggered by increased precipitation / snowmelt, leading to increased outflow from the lake and erosion of the outflow channel (partial breach of the moraine dam). This hypothesis is further supported by the lake being contained within a relatively large catchment (≈ 0.4 km²) for its size (<1000 m²). This event only affected a total area of about 1200 m² (both erosion and deposition) and attenuated immediately when reaching the gently-sloped main valley. This GLOF is among the smallest events in the inventory and helped us to illustrate the variety of GLOF triggers, mechanisms and also magnitudes.

5. Discussion

5.1. Incompleteness of existing GLOF records and GLOF timing analysis constraints

Our study highlights the incompleteness of global GLOF inventories in Peru and Bolivia, which to a large extent compile existing regional inventories. For instance, Carrivick and Tweed (2016) in their global GLOF inventory mention 15 GLOFs in Peru and 0 in Bolivia. Harrison et al. (2018) mention 28 Peruvian GLOFs (considering GLOFs from moraine-dammed lakes only), while our inventory contains 95 GLOFs from moraine-dammed lakes in Peru. Our study, thus, considerably extends existing sub-regional inventories and previously reported events.

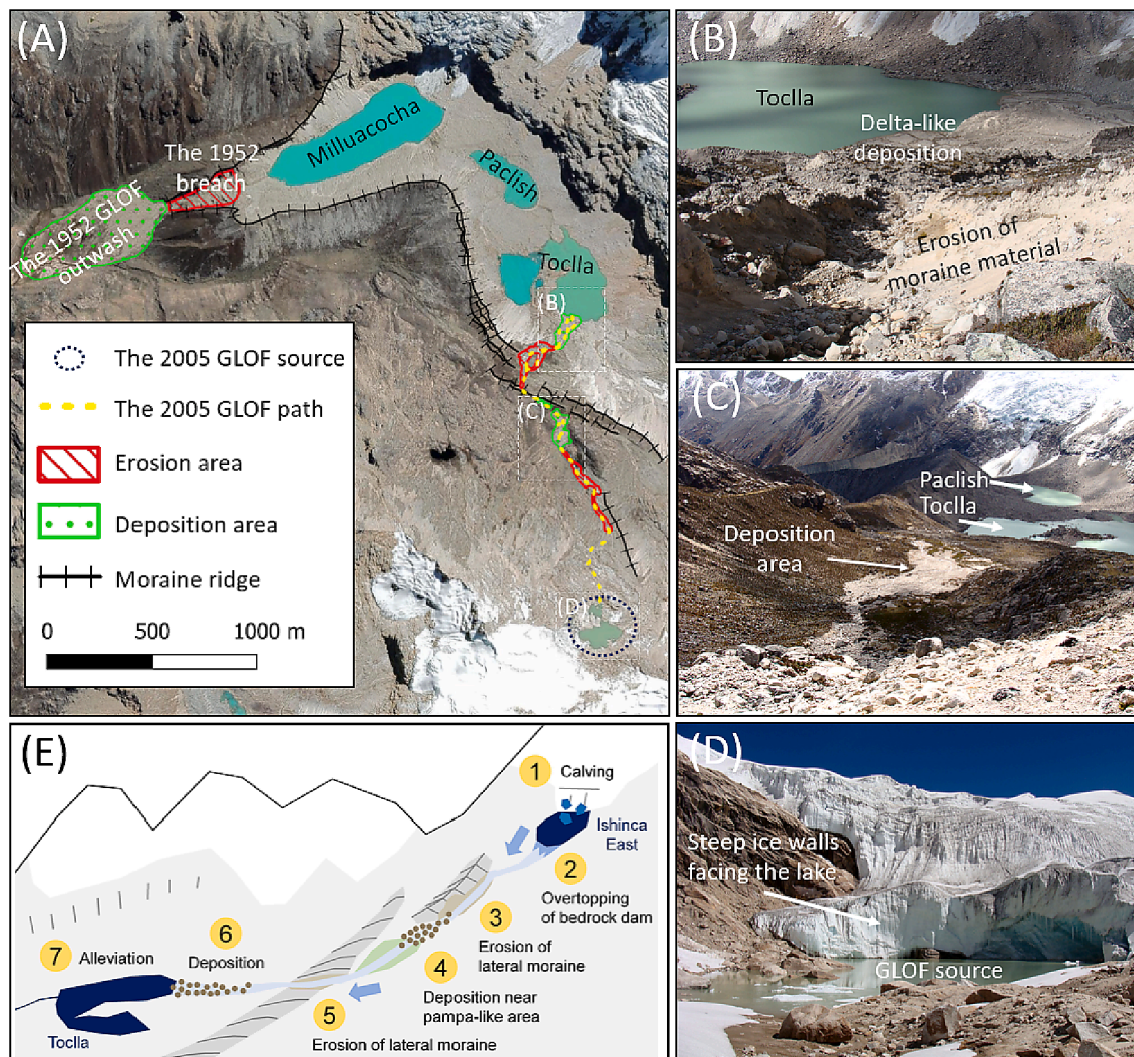


Fig. 9. The 2005 GLOF in the upper part of the Ishnica valley, Cordillera Blanca (Peru), for location see Fig. 4. (A) shows a satellite view of the upper part of the valley (Google Earth CNES/Airbus image from 22nd June 2019). (B) shows an eroded moraine slope and deposition in lake Toclla; (C) shows main part of the deposition behind the moraine ridge, with deposited boulders up to 0.4 m in diameter; (D) shows source lake with steep ice cliffs. (E) shows a schematic sketch illustrating the entire process chain. Field images: Adam Emmer.

Similar to this study, Nie et al. (2018) and Veh et al. (2019) highlighted the incompleteness of existing GLOF records over the Hindu Kush-Karakoram-Himalaya region by more than doubling the number of reported GLOFs from moraine-dammed lakes. Recently, Zheng et al. (2021) have also highlighted the incompleteness of GLOF records over the Third Pole region. Collectively, these studies show the value of conducting periodic and integrated GLOF reviews towards gaining a better understanding of GLOF characteristics in specific glacierised environments.

The mapping of past GLOFs is largely based on the identification of GLOF diagnostic features. These features are typically more distinct and longer lasting for higher magnitude GLOF events, making smaller GLOFs often more difficult to identify. As a result, documentary data sources may be biased towards containing only information about high magnitude events (see Veh et al., 2019), thus complicating our understanding of the temporal evolution of GLOFs in some regions. Our analysis for Peru and Bolivia indicates an increase in the frequency of type-C GLOF (i.e. low magnitude) events since 1970 (Fig. 7C). This observation suggests a greater number of GLOFs from bedrock-dammed lakes which are generally of lower magnitudes. GLOFs from bedrock-dammed lakes tend to be triggered by material falling into the lake, and almost always involve only partial lake drainage. The increase in the frequency of low

magnitude GLOFs may be indicative of the glacial retreat experienced throughout Peruvian and Bolivian Andes over recent decades, with glaciers now occupying terrain that is less topographically suitable for the formation of moraine-dammed lakes. However, there is also a possibility that the more subtle geomorphological changes that result from low magnitude events are more likely to be detected through analysis of satellite imagery (available from ~1970s), meaning that the trend towards more type-C / bedrock-dammed lake drainage is an artefact of data availability, rather than real. Equally, low magnitude events may be under-represented in the pre-1970 part of our inventory because they may not have been recorded or even noticed before the advent of satellite remote sensing. Further, the longevity of less-developed GLOF diagnostic features could be limited, although our case study does demonstrate that diagnostic features associated with even low magnitude GLOFs can leave an identifiable imprint in the landscape for decades (Section 4.4.2).

Overall, we do not claim our inventory is 100% complete and we are aware this is, in principle, an unachievable goal considering the difficulties in identifying those low magnitude events, the size of the study area and the need for laborious visual interpretation of remotely sensed time series images. Importantly, we present by far the most comprehensive unified inventory of GLOFs for Peru and Bolivia (and the

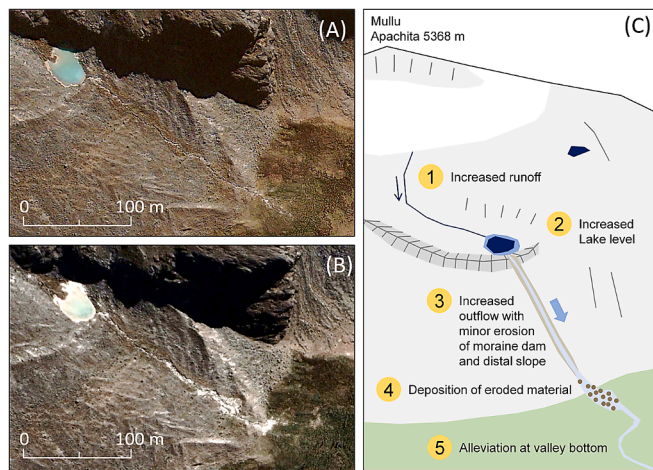


Fig. 10. An example of a low magnitude GLOF in the C. Real, Bolivia (for location see Fig. 4). (A) shows the lake before the GLOF (Google Earth Maxar Technologies image from 20th June 2010) while (B) shows the post-event situation with visible erosional and depositional areas located downstream the lake (Google Earth Maxar Technologies image from 18th May 2016). (C) summarises the process chain associated with this event.

Tropical Andes in general).

5.2. Implications for GLOF hazard and risk management and recommendations for future studies

The wide availability of remotely sensed datasets has facilitated the development of a range of approaches, aimed at assessing hazard and risk at localised and regional scales (e.g. Emmer and Vilfmeek, 2014; Rounce et al., 2016; Kougkoulos et al., 2018a; Allen et al., 2019; Veh et al., 2020; Islam and Patel, 2021). The value of these approaches relies on their ability to accurately represent key GLOF triggers and threshold parameters. Through field- and remote sensing-based observations, our understanding of these parameters has improved greatly throughout the 21st Century, with papers such as Emmer and Vilfmeek (2013) and Kougkoulos et al. (2018a) now providing comprehensive reviews of factors considered important when assessing the likelihood of GLOF occurrence. Despite this understanding, the relative importance of these factors in region-specific assessments is likely to be different, due to the differing topographic and climatic settings of glacierised environments and the varying magnitude of recent climate-induced glacier changes (GAPHAZ, 2017). In order to weigh these factors in a more meaningful manner, it is vital that detailed information about past GLOF events is available. The information regarding GLOF timing, spatial distribution, lake characteristics and trigger mechanisms presented here therefore represents an important first step towards the creation of national-scale GLOF hazard and risk assessments in both Peru and Bolivia. The creation of such assessments has been aided further by the recent publication of a nationwide inventory of glacial lakes for Peru (Wood et al., 2021).

Considering the analysis of the 160 GLOFs events presented, the following observations are deemed important in terms of prioritizing future glacial lake monitoring and the creation of GLOF hazard and risk assessment in the Tropical Andes:

- High magnitude GLOFs were mainly associated with failures of moraine dams of lakes in the proglacial phase of evolution (lake monitoring priority); once these lakes turn into the glacier-detached phase, GLOF susceptibility may be decreasing due to the increasing distance from the source and impact area of ice avalanches (see the conceptual model of Emmer et al., 2015). However, on longer timescales, the likelihood of rapid mass movements may then increase again as a result of the destabilisation of rock slopes above the

lake due to factors such as permafrost degradation (Haerberli et al., 2017), debuttressing (Knight and Harrison, 2013) and landslides in moraines (Klimeš et al., 2016; Emmer et al., 2020b). While numerous studies focus on climate change and permafrost degradation impacts on mass movements in general (Huggel et al., 2012; Stoffel and Huggel, 2012; Krautblatter et al., 2013; Gruber et al., 2017) and there are several recent examples of catastrophic process chains associated with changes in the cryosphere (Kääb et al., 2018; Shugar et al., 2021), these are rarely further linked to the occurrence of GLOFs from the broader spatial and temporal perspective, suggesting future research priority.

- Diverse types of rapid mass movements into glacial lakes (involving ice, rock or moraine material) were shown to trigger the majority of GLOFs that had a known cause, corroborating previous findings (Emmer and Cochachin, 2013); as such, monitoring slope stability / instabilities should be a priority for the timely identification of potential starting zones of GLOF process chains;
- Complete lake drainages are rare (<10% of cases) and should only be considered as the worst case scenario in GLOF modelling when it is justifiable (i.e. presence of likely high magnitude triggers, dam geometry and internal structure indicating possible top-to-bottom breach of moraines);
- Dam overtoppings are the most frequent GLOF mechanism (especially in recent decades); the total flood volume of dam overtopping-induced floods has been documented to be smaller, with a faster attenuation of the flood, compared to dam breach-induced floods (Sattar et al., 2021); therefore, bedrock-dammed lakes are generally less likely to produce high magnitude GLOFs (see also Emmer et al., 2020a);
- Dam freeboard is critical, yet is not always considered in GLOF hazard assessments or GLOF modelling studies. Dam freeboard acts as a natural mitigation element in the GLOF process chain (see the example of the Zapata, 2002 Safuna Alta GLOF (Hubbard et al., 2005; Klimeš et al., 2021) or the 2020 Salkantaycocha GLOF (Vilca et al., 2021)) and influences the volume of released water and GLOF magnitude. However, deriving dam freeboard of lakes without surface outflow is a challenging task, requiring field surveying;
- A recent study by Emmer et al. (2020a) showed that the topographical potential for the formation of new large lakes may be limited in mountain ranges where glaciers have already receded back to steeper slopes, which is the case in many of the Peruvian Cordilleras (Colonia et al., 2017; Drenkhan et al., 2018; Guardamino et al., 2019), Bolivia and in Northern Patagonia (Wilson et al., 2018);
- Considering the increasing distance of newly forming (mainly bedrock-dammed) lakes from the settled areas, and faster attenuation of overtopping-induced floods, the only possible trigger of high magnitude GLOF from these lakes would be a high-volume, rapid mass movement into the lake (e.g. Schaub et al., 2016; Haerberli et al., 2017); on the other hand, location in higher elevations may increase the overall energy and thus the run out of the process chain;
- Complex and site-specific understanding of process chains is needed for defining and modelling realistic GLOF scenarios. As a result, where possible, GLOF hazard mitigation measures should be designed and implemented on a basin-by-basin basis considering the inherent landscape (including lakes and glaciers and surrounding terrain) as an inter-connected system (Reynolds, 1992, 1998; Emmer et al., 2018);
- While research on physical mechanisms and process chains resulting in GLOFs has experienced a boom in recent years (Emmer, 2018), studies addressing GLOF vulnerability and other drivers and components of GLOF risk remains rare in the Tropical Andes (Carey, 2005; Hegglin and Huggel, 2008; Carey et al., 2012; GAPHAZ, 2017; Huggel et al., 2020). Therefore, it is recommended that future research should strive to reduce current knowledge gaps in these areas.

5.3. Climate change attribution

Climate attribution has been developed for several changing elements in earth systems, including for certain river floods (e.g. Pall et al., 2011) and extreme rainfall (e.g. Otto et al., 2015; Kumari et al., 2019). Recently, there have also been attribution experiments which demonstrate that glacier mass loss is clearly attributable to anthropogenic greenhouse gas forcing (e.g. Roe et al., 2021), and that the 1941 GLOF from Lake Palcacocha was similarly attributable (Stuart-Smith et al., 2021). However, many of these attribution studies have concentrated on single events and it remains uncertain whether complex hazard cascades, such as characterises many GLOFs, can also be attributable to anthropogenic climate change. In addition, attribution of GLOFs at global scales is likely to be difficult given the multivariate, contingent and non-linear causality of such rare events. To answer the question of whether GLOFs in Peru and Bolivia can be attributed to any one cause (including climate) is a debate beyond the scope of this paper. However, such an analysis would require a substantially more complete record of such events in an unforced climate (i.e. a clear understanding of the changes in magnitude and frequency of events over historic records) in order that assessments using fraction of attributable risk or other attribution techniques could be used.

6. Conclusions

We have created an inventory of GLOFs in the glacierized Cordilleras of Peru and Bolivia by the integration of in-depth literature review and analysis of documentary data, further enhanced by detailed geomorphological interpretation and analysis of remote sensing imagery with field validation. We compiled the information on 53 GLOFs from the literature and enlarged the inventory by mapping 107 GLOFs not mentioned previously. The key findings of our comprehensive Tropical Andean GLOF inventory can be summarised as follows:

- 160 GLOFs from 151 sites are inventoried, almost tripling the number of GLOFs found in the literature and documentary data, with new events particularly focussed in those less-inhabited Cordilleras
- On average 3 out of 100 existing lakes produced GLOFs (0.03 GLOFs per existing lake), with large variation in the order of two magnitudes among the studied Cordilleras
- The dominant source of GLOFs were moraine-dammed lakes ($n = 99$; 61.9%), susceptible to both dam overtopping and failure, followed by lakes dammed by combined dams ($n = 29$; 18.1%); and bedrock-dammed lakes ($n = 26$; 16.3%), other lake types are represented only marginally
- The dominant source and mechanisms of high magnitude GLOFs were failures of moraine dams, while dam overtopping-induced GLOFs are slightly more frequent than dam breach-induced GLOFs
- Most of the GLOF-producing lakes persisted ($n = 144$; 90.0%), 9 lakes produced repeated GLOF events and only 15 lakes drained completely as a result of the GLOF
- GLOF triggers are only known (or assumed) for a subset of 78 (mostly) previously documented events, revealing the dominant role of mass movements into lakes as the main GLOF trigger in the Tropical Andes
- We observed an increase in the frequency of high magnitude GLOFs originating from moraine-dammed lakes between the early record and 1970, and increased frequency of low-magnitude GLOFs originating from bedrock-dammed lakes and lakes with combined dams post-1970; however, these statistics rely on a limited number of cases with known timing ($n = 54$ from 1970, and a further 16 prior to this)

Based on these findings, we outline the following recommendations for future GLOF hazard assessments in the Tropical Andes: (i) we recommend quantitative statistical analysis of pre-GLOF conditions and lake characteristics for deriving regional GLOF susceptibility indicators

and their weights for future GLOF hazard assessment studies and reliable identification of GLOF-susceptible lakes; (ii) reflecting on variety of possible triggers and mechanisms, we recommend separate (independent) assessment procedures for different process chains considered; and (iii) relevant site-specific process chains should be taken into account in defining scenarios for GLOF modelling and hazard mitigation.

Data availability

The GLOF inventory of Peru and Bolivia created and analysed in this work is available as Supplementary material associated with paper.

Data / databases / online repositories

- ANA n.d. Autoridad Nacional del Agua (ANA) online repository. URL: <http://repositorio.ana.gob.pe/>
- EarthExplorer, n.d. United States Geological Survey Earth Explorer. URL: <https://earthexplorer.usgs.gov>
- EO browser, n.d. Sentinel Hub EO Browser, URL: <https://apps.seintinel-hub.com>
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- WOS, n.d. Clarivate Analytics Web of Knowledge database. URL: www.webofknowledge.com

Declaration of Competing Interest

The authors declare no conflict of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.gloplacha.2021.103722>.

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