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Contemporary glacial lakes in the Peruvian Andes

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ABSTRACT

Glacier recession in response to climate warming has resulted in an increase in the size and number of glacial lakes. Glacial lakes are an important focus for research as they impact water resources, glacier mass balance, and some produce catastrophic glacial lake outburst floods (GLOFs). Glaciers in Peru have retreated and thinned in recent decades, prompting the need for monitoring of ice- and water-bodies across the cordilleras. These monitoring efforts have been greatly facilitated by the availability of satellite imagery. However, knowledge gaps remain, particularly in relation to the formation, temporal evolution, and catastrophic drainage of glacial lakes. In this paper we address this gap by producing the most current and detailed glacial lake inventory in Peru and provide a set of reproducible methods that can be applied consistently for different time periods, and for other mountainous regions.

The new lake inventory presented includes a total of 4557 glacial lakes covering a total area of 328.85 km^2. In addition to detailing lake distribution and extent, the inventory includes other metrics, such as dam type and volume, which are important for GLOF hazard assessments. Analysis of these metrics showed that the majority of glacial lakes are detached from current glaciers (97%) and are classified as either embedded (i.e. bedrock dammed; ~64% of all lakes) or (moraine) dammed (~28% of all lakes) lakes. We also found that lake size varies with dam type; with dammed lakes tending to have larger areas than embedded lakes. The inventory presented provides an unparalleled view of the current state of glacial lakes in Peru and represents an important first step towards (1) improved understanding of glacial lakes and their topographic and morphological characteristics and (2) assessing risk associated with GLOFs.

1. Introduction

The recession of glaciers globally in response to climate warming has led to a dramatic increase in the size and number of supraglacial and proglacial lake systems (e.g. Rabatel et al., 2013; Haeberli et al., 2016; Shugar et al., 2020). In particular, post-Little Ice Age climatic warming has enhanced ice melt, leading to the development of a large number of glacial lakes behind ice dams, lateral and terminal moraines and within over-deepened de-glaciated valley bottoms (Quincey et al., 2007; Wilson et al., 2018). Glacial lakes are important globally and regionally as (1) they represent a considerable water resource (Loriaux and Casassa, 2013), (2) when in contact with or dammed by glaciers, they can have negative impacts on glacier mass balance (e.g. King et al., 2019), and (3) they are the source of glacial lake outburst floods (GLOFs; Richardson and Reynolds, 2000; Carrivick and Tweed, 2016; Harrison et al., 2018) which are considered to be the largest and most extensive glacial hazard

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in terms of disaster and damage potential (UNEP, 2007).

Glaciers in Peru have retreated and thinned considerably over recent decades (INAIGEM, 2018), prompting the need for greater monitoring of ice- and water-bodies contained within glacierised basins. Such efforts are important as they help inform local and national mitigation policies concerning the impacts of glacier retreat on water resources, mountain development, tourism and hazards. The availability of multi-temporal satellite imagery has greatly improved our understanding of glacier change and lake distribution in countries like Peru (e.g. Drenkhan et al., 2018), however, knowledge gaps remain, particularly in relation to the formation, temporal evolution, and drainage of glacial lakes.

This study aims to robustly identify, describe, and analyse the glacial lakes of Peru. In this paper we discuss the new lake inventory in detail and provide statistics regarding the different dam types, extent, and topographic setting of the glacial lakes of Peru. The methods used here are designed to be reproducible (allowing them to be applied to map glacial lakes in other glacierised regions) and will form the basis for assessing the evolution of lakes through time, as part of nationwide GLOF hazard assessments in Peru.

1.1. Glacial recession and GLOFs in the Peruvian Andes

The Peruvian Andes are home to 70% of the world's tropical glaciers covering an area of >1600 km^2 (WGMS, 2021.). In line with other areas of the Andes (Masiokas et al., 2009; Davies and Glasser, 2012; Rabatel et al., 2013), glaciers in Peru have, in general, undergone a sustained period of retreat and thinning since reaching their Little Ice Age Maximums (LIAMs) (Vuille et al., 2008; Hanshaw and Bookhagen, 2014; UGRG, 2014); with some cordilleras becoming completely deglaciated since the 1970s (e.g. Cordillera Barroso; INAIGEM, 2018; Supplementary Information 4 Fig. S1). Marked by lateral and terminal moraines, studies suggest that LIAM glacier positions in Peru extended some >2000 m down valley of their 21st Century extent, with length varying according to localised topographic and climate settings (Drenkhan et al., 2018; Emmer et al., 2021; Supplementary Information 5 Table S1). The extent of glacial retreat across the Peruvian Andes over recent decades has led to concerns that the deglaciation discharge dividend in this region may have already peaked (Baraer et al., 2012); placing renewed emphasis on efforts to quantify both glacier health and lake distribution in the region.

Glacial lake outburst floods (GLOFs) are known for their extreme peak discharges (e.g. Clague et al., 2012) and are among the most important geomorphic agents in deglaciating mountain ranges across the globe; presenting a serious natural hazard (Reynolds, 1992; Carrivick and Tweed, 2016). As well as increasing the exposure of mountain societies to GLOF hazards, glacier retreat-induced formation and evolution of glacial lakes raises GLOF disaster risk concerns; especially in low-income countries of high Asia and South America (Emmer, 2018). While historical GLOF records, although incomplete, allow us to reveal general and regionally specific GLOF susceptibility indicators (e.g. lake, dam and surrounding geomorphic characteristics; see Kougkoulos et al., 2018), reliable evaluation of GLOF susceptibility still requires up to date lake inventory data with quantitative as well as qualitative lake characteristics.

1.2. Glacier lake inventories

Globally, there has been a recent increase in the number of available lake inventories; partly due to the impact that lakes have on continental carbon cycles, biogeochemical processes, water resources and GLOF hazards (Emmer et al., 2020; Verpoorter et al., 2014). From the use of early aerial images (e.g. Emmer et al., 2016; Viani et al., 2016) to the availability of long time-series global satellite data (such as the Landsat missions from 1972 onwards; Shugar et al., 2020), open source and "big data" cloud computing has expedited the creation of lake inventories for individual basins (Mahdianpari et al., 2019; Kumar et al., 2020), wider regions (e.g. Mosquera et al., 2017; Wilson et al., 2018; Wang et al., 2020; Worni et al., 2013), globally (Verpoorter et al., 2014; Shugar et al., 2020), and their evolution through time. This has allowed researchers to identify changes in lake size (and therefore estimate changes to lake volume) in order to better constrain and model the hydrological response of glaciers to climate change (e.g. Shugar et al., 2020).

A number of historic sub-national lake inventories exist for the Peruvian Cordilleras (e.g. Cordillera Blanca: Emmer et al., 2016, 2020, Vilímek et al., 2016; Vilcanota-Urubamba basin: Drenkhan et al., 2018), and provide some estimates of lake volume and lake area-depth-volume relationships (e.g. Cordillera Blanca: Muñoz et al., 2020) and future lake growth potential (e.g. Colonia et al., 2017; Drenkhan et al., 2018). The inventory of the Instituto Nacional de Investigación en Glaciares y Ecosistemas de Montaña (INAIGEM, 2021; henceforth the inventory is referred to as INAIGEM) is the only existing lake inventory to cover all 20 glaciated cordilleras. This inventory covers an observation period of 2016 and uses a variety of satellite sensors (Supplementary Information 5 Table S2). The Autoridad Nacional del Agua inventory (ANA, 2014; henceforth referred to as ANA) covers 19 cordilleras (with the exception of Cordillera Barroso) and an observation period of 2001–2010. This inventory also uses a variety of different sensors, which vary across the cordilleras (Supplementary Information 5 Table S3). The lake inventory by Emmer (2016, henceforth referred to as Emmer) covers the Cordillera Blanca and was generated using a variety of remote sensing techniques, covering the period 1948–2018. These inventories (ANA, INAIGEM and Emmer) include many important metrics for understanding lake evolution and GLOF potential (Table 1) and are presented in Supplementary Information 1 as they will be used as comparisons for this study.

Although these previous inventories are very valuable, for robust quantification of glacial lake changes through time it is important for there to be internal consistency in the methods and data sources used to derive the lake outlines. This is the gap that the current study aims to fill.

2. Methods

This paper principally presents a new glacier lake inventory for the Peruvian Cordilleras (henceforth projectGLOP). A full account of the methods applied are summarised in Fig. 2 and detailed in Supplementary Information 2.

Initially, glacier lakes were defined as all lakes within 3 km of existing glaciers (using the GLIMS/Randolph Glacier Inventory v6.0; GLIMS, 2019). This 3 km buffer represents an assumed LIAM, which was obtained through substantial review of relevant literature (Supplementary Information 5 Table S1; Supplementary Information 2.1.1). Lakes within the LIAM buffer were manually digitised using a combination of Landsat Thematic Mapper Tier 1 data (TMT1; Dykstra and Owen, 2017), derived Normalised Difference Water Index and Normalised Difference Snow Index data, as well as high resolution Quantum Geographic Information System QuickMapServices (NextGIS, 2015) satellite data (Fig. 2; Supplementary Information 2.1.2 and 2.1.3). Where available, 2019 Landsat images with <10% cloud cover were used, in a number of limited cases data from 2018 and 2017 were used for lake digitisation (see Fig. 2, Supplementary Information 2.1.2 and Supplementary Information 4 Fig. S3). A lake digitisation uncertainty analysis was additionally performed to ascertain the repeatability of the methods described; this analysis involved comparison of lake outlines mapped by three separate users (see Supplementary Information 2.1.3). Important metrics (Table 1) were recorded in order that the inventory is applicable across a range of future analyses. In terms of the lake dam type, we use broad definitions of "dammed" (which includes moraine dammed lakes), "embedded" (bedrock dammed lakes) and "unclassified" for lakes dammed by landslides, as well as lakes in which the dam type cannot be identified. We also differentiate between lakes in contact with existing glaciers, and those which are detached.

Lake area was calculated for lakes in the projectGLOP inventory and

Table 1
Metrics that were recorded in ANA, INAIGEM, Emmer and the new projectGLOP (described in this study) lake inventories.

Metric	Details	Sample technique (projectGLOP)	project GLOP	Emmer	INAIGEM	ANA
ID	Unique ID for all mapped lakes	ID automatically generated in QGIS using the field calculator	yes	yes	yes	yes
lake_type	Type based on dam type. We give broad definitions of “dammed” (which includes moraine dammed lakes), “embedded” (bedrock dammed lakes) and “unclassified” for lakes dammed by landslides, as well as lakes in which the dam type cannot be identified.	Visual interpretation of remotely sensed imagery by the digitiser	yes	yes		
l_sub_type	In contact or not in contact with ice	Identified by contact with the GLIMS (2019) polygons	yes	yes		
Outflow	Lake outflow	Identified by the digitiser based on visible outflow on the ESRI, Google or Bing aerial images through QuickMapServices in QGIS	yes	yes		
Notes	Any notes deemed important	Identified by the digitiser	yes	yes		
Digitised	Username of person digitising lake	Signed by the digitiser	yes		yes	
Year	Year of image used	Year (date) of imagery used	yes		yes	yes
Sensor	e.g. Landsat, ASTER, Liss III, etc	Identified by the digitiser	yes		yes	yes
area_utm18	Lake area (in m^2; utm18)	Calculated using the Field Calculator in QGIS	yes	size	yes	yes
area_utm19	Lake area (in m^2; utm19)	Calculated using the Field Calculator in QGIS	yes	category	yes	yes
area_utm	Lake area (in m^2; in either utm18 or utm19)	Compilation of the area_utm18 and area_utm19 data	yes		yes	yes
volume_m3	Lake volume from Guardamino and Drenkhan (2016) and ANA (2014) to define scaling relationships.	Calculated based on available data (see Supplementary Information 2.2.3)	Yes			yes
depth_m	Lake depth from Guardamino and Drenkhan (2016) and ANA (2014)	Manually input into the inventory	Yes			yes
ele30mean	Lake ele30mean	Calculated in QGIS using the raster Zonal Statistics tool	yes	yes	yes	yes

uncertainty analyses performed to estimate (1) by how much lake area is over/under-estimated using 30 m resolution Landsat TMT1 data, and (2) how many small lakes (<900 m^2) are excluded (Supplementary Information 2.2.1). Statistical analyses were performed to gain a picture of lake elevation across Peru (Supplementary Information 2.2.2). We calculated lake volume based on derived scaling relationships (Supplementary Information 2.2.3). Finally, we compared the projectGLOP lake inventory with a number of existing inventories for the Peruvian Cordilleras (Supplementary Information 2.3).

3. Results and Discussion

3.1. 3.1 projectGLOP lake inventory

Our glacial lake inventory for the Peruvian Cordilleras, comprises a total of 4557 glacial lakes within 3 km of existing glaciers (based on the GLIMS/Randolph Glacier Inventory v6.0; GLIMS, 2019; Raup et al., 2007). The majority of lakes are detached from current glaciers (97%; Table 2). If we consider all lakes, the majority of these are either embedded (~64%) or dammed (~28%) lakes, with the remaining 5% falling into the unclassified category (see Table 1). These unclassified lakes include 17 landslide dammed lakes (10 in the Cordillera Blanca,

Table 2
Lake counts for each cordillera (please refer to Fig. 1) by dam type and sub-type (not/in contact with ice). “Dammed” includes moraine dammed lakes, bedrock dammed lakes are “embedded”. Lakes dammed by landslides are included in the “unclassified” category, as well as lakes in which the dam type cannot be identified due to unclear satellite images. Supraglacial lakes are not included in the inventory as they are influenced by seasonal variation in drainage.

Cordillera		Lat/ Lon	Total	Lake type: Embedded, Lake sub-type: in contact with ice	not in contact with ice	Dammed: in contact with ice	not in contact with ice	Unclassified: in contact with ice	not in contact with ice	Lake sub-type total: in contact with ice	not in contact with ice
Cordilleras del norte	Blanca	77.87 W,	803	21	424	12	286	1	59	34	769
	Huallanca	8.06 S to	69	3	55	0	9	0	2	3	66
	Huayhuash	76.78 W,	129	5	46	2	72	0	4	7	122
	Raura	10.67 S	245	3	164	0	54	0	24	3	242
Cordilleras del centro	Huagoruncho	75.92 W,	145	1	74	0	65	0	5	1	144
	La Viuda	9.80 S	442	3	276	0	138	0	25	3	439
	Huaytapallana	to	373	6	244	3	115	0	5	9	364
	Central	74.52 W,	509	18	340	2	98	0	51	20	489
	Chonta	13.62 S	212	0	188	0	22	0	2	0	212
Cordilleras del sur	Urubamba	72.53 W,	139	1	108	0	25	0	5	1	138
	Vilcabamba	12.61 S	183	7	107	0	59	0	10	7	176
	Vilcanota	to	490	13	233	28	199	2	15	43	447
	Carabaya	69.40 W,	590	7	496	2	68	0	17	9	581
	Apolobamba	14.88 S	142	2	104	1	23	0	12	3	139
	Huanzo		54	0	42	0	9	0	3	0	54
	Chila		13	0	6	1	6	0	0	1	12
	Ampato		19	1	13	0	4	0	1	1	18
Total			4557	91	2920	51	1252	3	240	145	4412

two in C. Central, and one in each of C. Apolobamba, C. Carabaya, C. Huallanca, C. La Viuda and C. Vilcanota), one ice dammed lake (in C. Vilcanota), with 222 lakes marked as unclassified as dam type was not identified using readily accessible (ESRI, Bing and Google) satellite imagery. Only 3% of lakes remain in contact with ice; 63% of these are embedded, 35% are dammed and the remaining 2% are unclassified (Table 2). The expansion of glacial lakes often occurs in response to glacial recession, when low gradient glacier termini retreat back into over-deepened basins. The fact that only 3% of lakes remain in contact with ice is of significance as it may limit the growth of current lakes into the future (see Wilson et al., 2018).

3.2. Lake inventory statistics

The following sections present an analysis of the projectGLOP lake inventory in terms of important characteristics and distributions; specifically, lake area (3.2.1), lake elevation (3.2.2), lake bathymetry (3.2.3), and finally we contextualise this new inventory alongside three existing inventories for Peru (3.3.4). Within each section we consider (1) variation across the Peruvian Cordilleras; (2) lake connectivity to existing glaciers; and (3) variation relating to differences in dam type. We consider each of these to have important implications for both water resources and GLOF hazards.

3.3. projectGLOP lake area

Knowledge regarding the areal extent of existing glacial lakes in Peru is important, in respect to GLOFs, as it provides a basis for calculating the effective water volume of individual lakes (which can influence the magnitude and duration of GLOF events) and assessing potential likelihood of GLOF trigger and threshold parameters related to the lake dam and the surrounding geomorphic features (Reynolds, 2014; Kougkoulos et al., 2018). Overall, we found that the Cordilleras Vilcanota, Carabaya, La Viuda and Blanca account for >50% of glacial lake area across Peru (Table 3). In terms of dam type, embedded lakes cover the largest area (Table 3), but this varies across the cordilleras. In general, we found that cordilleras that contained a larger extent of dammed lakes than embedded lakes tended to be more glacierised (INAIGEM, 2018; Supplementary Information 4 Fig. S1).

Between the cordilleras, the distribution of lake size varies (Fig. 3A); pairwise Wilcox tests show that area distributions are statistically different between some cordilleras (e.g. Carabaya and Blanca), while others present similar distributions (e.g. Blanca and Central; Fig. 3A; Table S5). There are a number of larger lakes that represent outliers in the distribution of lake areas across the majority of the cordilleras (Fig. 3A). In total, there are 33 lakes which are greater than 1 km^2 in area. They lie in Vilcanota ($n = 3$), Raura ($n = 3$), La Viuda ($n = 5$), Huaytapallana ($n = 1$), Chonta ($n = 2$), Central ($n = 7$), Carabaya ($n = 6$), Blanca ($n = 1$) and Apolobamba ($n = 4$). Two of these lakes (one in Vilcanota and one in Apolobamba), are greater than 10 km^2, and are recorded here as they lie (at least partly) within the 3 km buffer (described in Supplementary Information 2.1.1). It is likely that these lakes are older than the LIAM, however, they are located in close proximity to existing glaciers (i.e. <3 km) and so have been included within the inventory.

Table 3
Calculated lake areas for each of the studied cordilleras in Peru and separated by dam type.

	Dammed (km^2)	Embedded (km^2)	Unclassified (km^2)	Total (km^2)
Blanca	19.64	15.41	3.68	38.72
Huallanca	0.77	0.82	0.10	1.68
Huagoruncho	6.53	5.09	0.70	12.33
Huayhuash	5.55	1.27	0.11	6.92
Raura	6.17	9.65	0.54	16.36
La Viuda	22.22	23.93	0.40	46.56
Huaytapallana	7.50	11.19	0.08	18.77
Central	14.40	20.50	3.02	37.92
Chonta	0.29	10.69	0.08	11.06
Urubamba	0.72	2.49	0.11	3.32
Vilcabamba	1.77	2.93	0.11	4.81
Vilcanota	13.07	5.59	30.67	49.33
Carabaya	12.63	23.90	10.33	46.86
Apolobamba	9.17	6.80	14.91	30.88
Huanzo	0.13	1.34	0.17	1.64
Chila	0.59	0.39	–	0.97
Ampato	0.02	0.71	0.01	0.73
Total	121.15	142.68	65.03	328.86

Cordilleras which have seen the biggest loss of glacier extent (by >80% since the 1950's) include La Viuda, Chonta, Huanzo, Chila and La Raya (INAIGEM, 2018; Supplementary Information 4 Fig. S1); Huanzo and Chonta are the only cordilleras in which all glacier lakes are detached from current glaciers (Table 3 and Fig. 3B). For each cordillera, Kruskal-Wallis rank sum tests were performed to see if there is a significant difference between lake area and contact with existing glaciers. Where a significant difference was found, larger lakes were in contact with existing glaciers in Cordilleras Vilcanota and Blanca, whilst lakes in La Viuda are larger when detached from glaciers (Fig. 3B and Supplementary Information 5 Table S5); for all other cordilleras, no significant difference was found between the two groups, possibly due to low recorded lake numbers in contact with ice (Table 2).

Lake dam type was investigated to see if there was a significant difference between lake size recorded between different dam types (Fig. 3C). Most of the significant differences in lake size were between embedded and dammed lakes (in 11 of the cordilleras; Supplementary Information 5 Table S7). In all cases, dammed lakes are significantly bigger than embedded lakes (for the 11 cordilleras where significant differences were found; Fig. 3C and Table S7); this is an important finding for understanding future GLOF potential and hazard in these cordilleras.

3.4. projectGLOP lake elevation

Lake elevation was found to vary depending on the topography of the respective cordilleras. Overall, lakes were not found at the highest elevations of any cordillera due to limited topographic opportunity from the presence of both glaciers and steep slopes (Fig. 4A). Instead, the majority of lakes were found to be constrained within a limited elevation range of between ≅ 4500 m asl and ≅ 4800 m asl (Fig. 4A). The highest elevation recorded for any lake is an embedded lake in Ampato (5660 m asl) whilst the lowest elevation lake is in Carabaya (at 3686 m asl). Statistically, there is a significant difference between the lake elevation distribution and the random sample of points across the cordilleras (Kruskall-Wallace test; p-value <0.01; Fig. 4A).

In terms of lake sub-types, lakes in contact with ice were found to be at higher elevations in all cordilleras in which they are present. There is a significant difference in elevation between lakes in contact with glaciers and those which are glacier-detached in the Cordilleras Blanca, Carabaya, Vilcanota, Central, Vilcabamba, Huayhuash, La Viuda, Raura and Huallanca (p-value <0.01) and Apolobamba (p-value <0.05) (Fig. 4B and Table S8).

In terms of dam type, results reveal a significant difference in lake elevation between embedded and dammed lakes in nine of the glaciated cordilleras (Fig. 4C and Table S9). In Vilcanota and Huaytapallana, dammed lakes are found at significantly higher elevations than embedded lakes; whilst embedded lakes are found at higher elevations than dammed lakes in Huayhuash, La Viuda, Raura, Huallanca, Huagoruncho and Urubamba (Fig. 4C and Table S9). Some of these cordilleras have shown a > 70% reduction in glacial extent since the 1960s: La Viuda (>85% loss in glacial area), Huallanca (~75%), Huagoruncho and Urubamba (<70%); this rapid deglaciation is potentially associated with the difference in elevation between the dammed and embedded lakes observed (Fig. 4C) but the relationship between dam type and elevation is complex, with distributions varying between cordillera (Fig. 4C and Table S9).

3.4.1. Bathymetry and lake volume

Bathymetry data for the Cordillera Blanca (Guardamino and Drenkhan, 2016; ANA, 2014) were used to explore existing scaling relationships (Table 4) between lake depth and width (Fig. 5A) and lake area and volume (Fig. 5B). Both area-depth (AD) and area-volume (AV) scaling relationships were calculated for all lakes through the application of log-linear models in R Statistical Software; scaling relationships were calculated for all lakes (Fig. 5A and B), and were then a subset based on dam type (see Supplementary Information 4 Fig. S4).

Table 4
A selection of scaling relationships used to estimate lake volume and the estimates for this study; a full discussion of the results and error can be found in Cook and Quincey (2015) and Muñoz et al. (2020). Where *D* is the mean lake depth (in metres; for Muñoz et al., 2020 see notes); *A* is the surface area of the lake (in m^2); *V* is lake volume (in m^3).

Study	Region	Estimation of lake depth (m)	Estimation of lake volume (m^3)	Notes
Evans (1986)	Canada	$D = 0.035 A^{0.5}$	$V = 0.035 A^{1.5}$	Cited in Muñoz et al. (2020).
O'Connor et al. (2001)	British Columbia		$V = 3.114 A + 0.0001685 A^2$	Cited in McKillop and Clague (2007) and Cook and Quincey (2015).
Huggel et al. (2002)	Global	$D = 0.104 A^{0.42}$	$V = 0.104 A^{1.42}$	Huggel et al. (2002) show lake depth and area are correlated for a combination of ice dammed, moraine-dammed and thermokarst lakes. *D/A* $R^2 = 0.916$. Established relationship which has been applied directly (or modified) to estimate lake volume; but not over a range of lake dam types.
Wang et al. (2012)	Himalayas	$D = 0.087 A^{0.434}$	$V = 0.0354 A^{1.3724}$	Cited in Muñoz et al. (2020). *D/A* $R^2 = 0.503$; *V/A* $R^2 = 0.919$
Loriaux and Casassa (2013)	Global	$D = 0.2933 A^{0.3324}$	$V = 0.2933 A^{1.3324}$	Cited in Muñoz et al. (2020). *V/A* $R^2 = 0.96$.
Cook and Quincey (2015)	Global	$D = 0.1217 A^{0.4129}$	$V = 0.1217 A^{1.4129}$	Based on the re-plot of data presented in Huggel et al. (2002). *D/A* $R^2 = 0.38$; *V/A* $R^2 = 0.91$.
Kapitsa et al. (2017)	Kazakhstan	$D = 0.036 A^{0.49}$	$V = 0.036 A^{1.49}$	Cited in Munōz et al. (2020).
Muñoz et al. (2020)	Cordillera Blanca	$d = 0.041 * W + 2$	$V = A * d$	Where *d* is the linear regression between mean lake depth and width (*Md_Wi* in Muñoz et al., 2020); *W* is the lake width.
This study	Cordillera Blanca	$D = 0.38 A^{0.394}$	$V = 0.126 A^{1.412}$	All lakes: *D/A* $R^2 = 0.374$; *V/A* $R^2 = 0.825$.
		$D = 0.685 A^{0.345}$	$V = 0.249 A^{1.364}$	Dammed: *D/A* $R^2 = 0.333$; *V/A* $R^2 = 0.848$.
		$D = 0 A^{3.047}$	$V = 0 A^{4.65}$	Embedded: *D/A* $R^2 = 0.964$; *V/A* $R^2 = 0.98$.
		$D = 0.004 A^{0.765}$	$V = 0.006 A^{1.643}$	Unclassified: *D/A* $R^2 = 0.886$; *V/A* $R^2 = 0.824$.

Relationships derived for the AD scaling tend to be weak (low R^2; Table 4), and the AD scaling exponents calculated for this study (for all lakes) is significantly different to those derived from similar studies (outside of the 95% confidence interval; Fig. S5). When lakes are subset by dam type (Fig. S4), the AD relationship (here judged by the R^2 value) improves for unclassified and embedded lakes (although this is largely a function of lower lake numbers in the case of embedded lakes).

The AV scaling relationship calculated for all lakes was slightly weaker than similar studies ($R^2 = 0.825$; Table 4 and Fig. 5B), however the scaling exponents were similar to that of other similar studies (falling largely within the 95% confidence interval; Fig. 5C). A recent study for the Cordillera Blanca (Muñoz et al., 2020) found the AV approach less effective than deriving volume from area and a ratio between mean lake depth and width; as mean lake depth observations were not available for this study, we have relied on estimates of widely applied existing relationships (e.g. Shugar et al., 2020).

The calculated AV scaling exponents (Table 4) were applied across the entire projectGLOP inventory (1) for all lakes irrespective of dam type (Fig. 6), and (2) using the calculated exponents for dammed, embedded and unclassified lakes (Supplementary Information 4 Fig. S5; Table 4). As with calculated lake area (3.2.1), there are a number of outliers in the data. From the calculated estimates of lake volume, lakes in the Cordillera Vilcanota contain the highest volume of water, with Apolobamba containing the second highest volume (Table 5); however, one large lake in Vilcanota (4.5 km^3) accounts for ~90% of the total water volume; in Apolobamba the largest lake (1.7 km^3) accounts for ~70% of the total; both lakes were possibly formed pre-LIAM but are located within 3 km of existing glaciers.

3.5. Lake inventory comparisons

The projectGLOP database provides a current (2019) picture of the nature of lakes across the Peruvian cordilleras, but there are also a number of other existing inventories for Peru. INAIGEM covers all 20

Table 5
Estimates of total lake volume for each cordillera based on the scaling exponents derived for this study (Fig. 5). Presented here are the volume estimates derived from all lakes irrespective of dam type (*All lakes*), with these data also separated by dam type (*Dammed lakes*, *Embedded lakes* and *Unclassified lakes*).

Cordillera	Volume (km^3)			
	All lakes	Dammed lakes	Embedded lakes	Unclassified lakes
Blanca	0.79	0.44	0.27	0.08
Huallanca	0.02	0.01	0.01	0.00
Huagoruncho	0.25	0.13	0.10	0.02
Huayhuash	0.14	0.12	0.02	0.00
Raura	0.49	0.19	0.29	0.01
La Viuda	1.87	1.03	0.84	0.00
Huaytapallana	0.40	0.20	0.19	0.00
Central	1.12	0.46	0.60	0.07
Chonta	0.42	0.00	0.42	0.00
Urubamba	0.04	0.01	0.03	0.00
Vilcabamba	0.06	0.02	0.04	0.00
Vilcanota	5.06	0.43	0.08	4.55
Carabaya	1.73	0.52	0.45	0.77
Apolobamba	2.42	0.52	0.24	1.66
Huanzo	0.02	0.00	0.02	0.00
Chila	0.02	0.02	0.01	
Ampato	0.02	0.00	0.02	0.00
Total	14.87	4.09	3.62	7.17

cordilleras, ANA covers 19, and Emmer provides an inventory for the Cordillera Blanca (Fig. 1). The methods and satellite imagery (see Supplementary Information 5 Tables S1 and S2) used to collate these inventories differ, which has implications for the applicability of the inventories over different time periods as it will depend greatly on the availability of similar resolution satellite imagery to understand past lake fluctuations. Here, we use consistent methods (Supplementary Information 2.1) and data (Landsat missions) in order that the projectGLOP inventory is directly comparable through time (back to 1972). In terms of lake numbers, the INAIGEM dataset, which was digitised using high resolution satellite images (Supplementary Information 5 Table S2), has the highest number of recorded lakes (Table 6), whilst the ANA inventory consistently records the lowest lake numbers (Table 6) despite using a combination of both low (30 m) and high (10 m) resolution satellite images (Supplementary Information 5 Table S3).

The range of lake areas between each inventory is consistent with the different methods and satellite imagery used to compile each of the different lake inventories (Fig. 7). Lakes in the INAIGEM inventory are consistently smaller than the ANA and projectGLOP inventories due to the higher resolution imagery being used for lake digitisation; which is matched by the higher number of lakes recorded (Table 6). Despite using a range of both high- and low-resolution satellite images, the lake areas recorded in the ANA inventory are consistently larger than the other inventories; further shown by the significant difference between the ANA inventory and most other inventories (Table 7).

Lake elevation was available within the ANA and Emmer inventories. Lake elevation distributions for these and the projectGLOP inventory were compared using Wilcoxon rank sum tests; elevation was found to be significantly different between the three inventories (Fig. 8). Reasons for this could include the different methods used to compile the inventories, differences in the number of lakes recorded (Table 6) or as a result of lakes having changed shape, size, emerged or been drained throughout the different time periods covered by each of the inventories.

Table 6
Lake counts for each inventory by cordillera. Data for the ANA, INAIGEM and Emmer inventories have been subset from the original data to include only lakes which occur within the 3 km buffer (Supplementary Information 2.1.1).

Cordillera	ANA	Emmer	INIAGEM	projectGLOP
Blanca	385	711	882	803
Huallanca	28	–	74	69
Huagoruncho	102	–	206	145
Huayhuash	72	–	172	129
Raura	133	–	513	245
La Viuda	212	–	583	442
Huaytapallana	192	–	614	373
Central	266	–	490	509
Chonta	96	–	127	212
Urubamba	81	–	241	139
Vilcabamba	100	–	269	183
Vilcanota	187	–	1250	490
Carabaya	366	–	661	590
Apolobamba	47	–	179	142
Huanzo	32	–	54	54
Chila	10	–	19	13
Ampato	7	–	39	19
Total	2316	711	6373	4557

Comparisons between these inventories highlight the impact of differing methodologies on the mapping of glacial lakes in the same area. For the purposes of GLOF hazard assessments, it is important that temporal records of glacier lake changes are available, which are cross-comparable (e.g. Wilson et al., 2018). We would therefore recommend:

(1) A clearly defined glacial lake sampling strategy. This needs to be based on an appropriate understanding of the glacial history of the region (which we propose based on previous literature; Supplementary Information 5 Table S1). It was clear from comparing the inventories

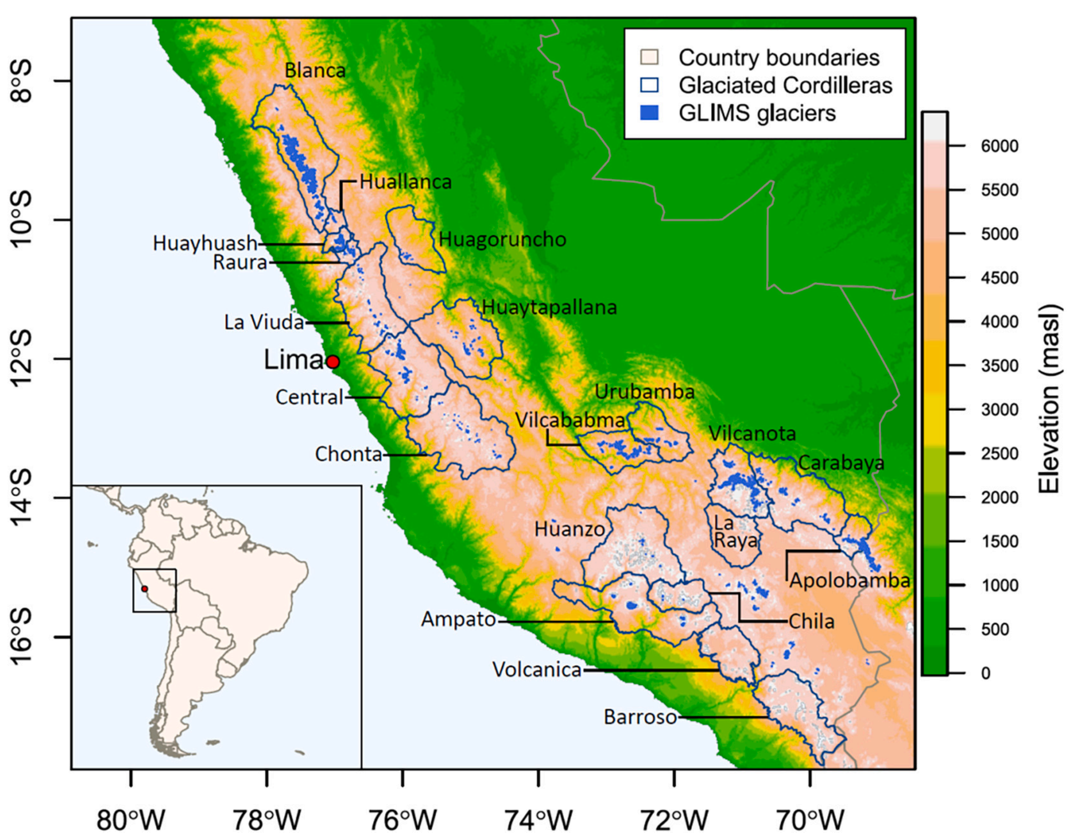

Fig. 1. Of the 20 Peruvian cordilleras shown, only 17 are currently glaciarised (GLIMS, 2019; La Raya, Volcanica and Barroso are not currently glacierised). For this paper, lakes in the unknown regions (i.e. lakes that fall outside of the 20 named cordilleras; $n = 309$) have been removed from the presented analyses.

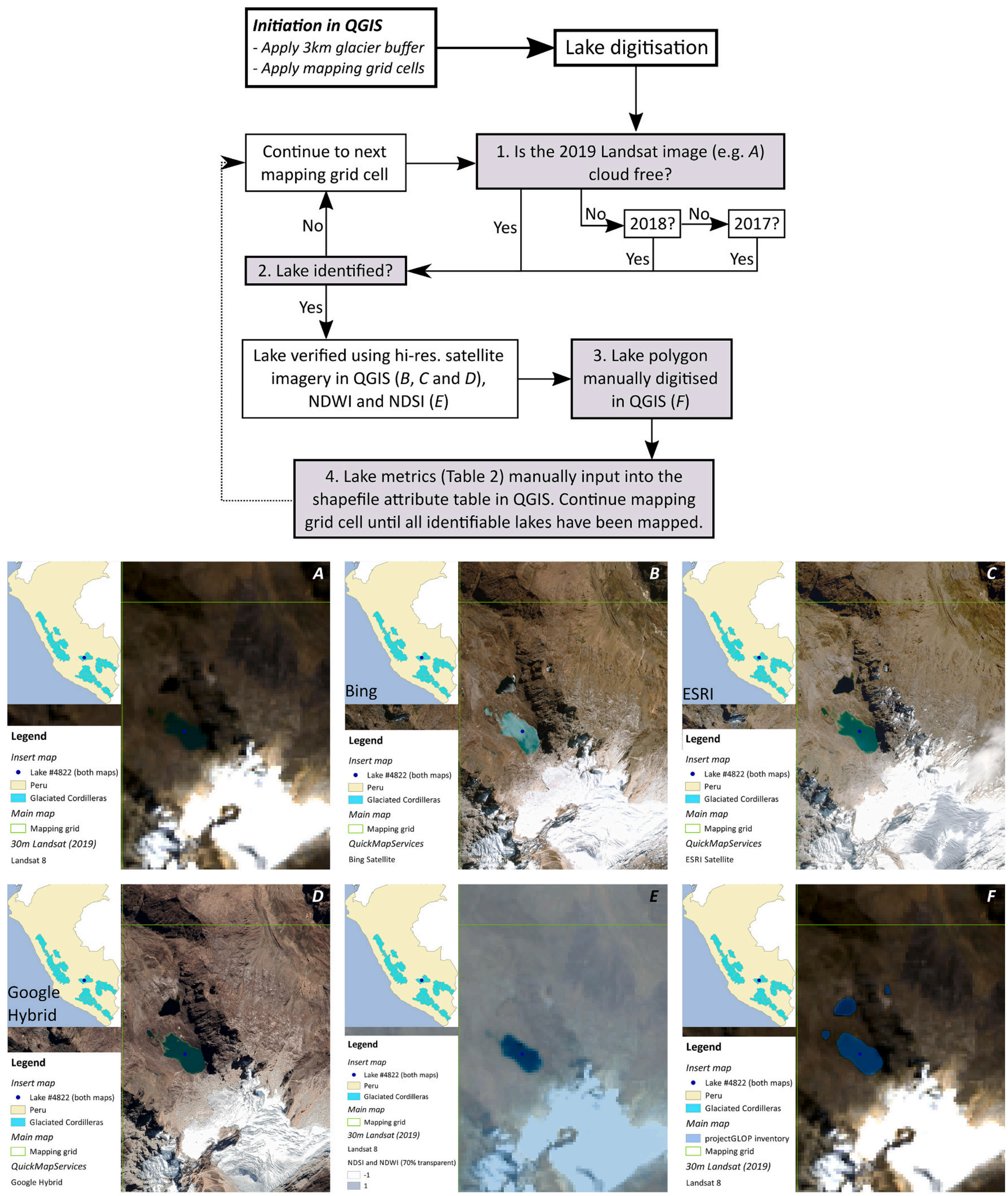

Fig. 2. Flow chart showing the lake identification and manual digitisation. The bottom inserts (A-F) centre over lake #4822, Cordillera Vilcabamba, to provide an example of the Landsat data (A; Supplementary Information 2.1.2), NDSI and NDWI calculations (E; semi-transparent 70% over the Landsat data; Supplementary Information 2.1.2 Eq. 1 and 2 respectively). Secondary datasets used for lake identification include the QGIS QuickMapServices plugin (B, C and D) used during lake digitisation. Also shown is an example of the digitised lakes (F; Supplementary Information 2.1.3).

that the number of glacier lakes included depended on the different strategies used; this needs to be consistent to facilitate future glacial lake hazard investigations.

(2) Both the spatial and temporal resolution of the satellite data need to facilitate cross-comparability. Ideally, high resolution imagery should be used, however, the temporal and spatial coverage of these data are limited compared to low resolution imagery, such as Landsat. For adequate assessment of changes in lakes through time, individual inventories need to represent distinct time stamps. To compile the ANA inventory, for example, 10 years of mixed high- and low-resolution data were needed to map 19 of the cordilleras (Supplementary Information 5 Table S3). As such we feel Landsat offers the best option in terms of both resolution and longevity, and its applicability can be augmented with the use and consultation of high-resolution options available (e.g. within Google Earth Engine).

(3) Lake inventories in high-mountain regions should use a manual mapping approach. Our use of NDWI and NDSI highlighted the advantages of automated classification methods, as they allow for the rapid mapping of large areas. However, these often require extensive and time-consuming manual correction due to issues with (e.g.) cloud cover, shadow and snow/ice effects (Shugar et al., 2020), with the potential to miss lakes altogether. Due to these issues, manual methods continue to

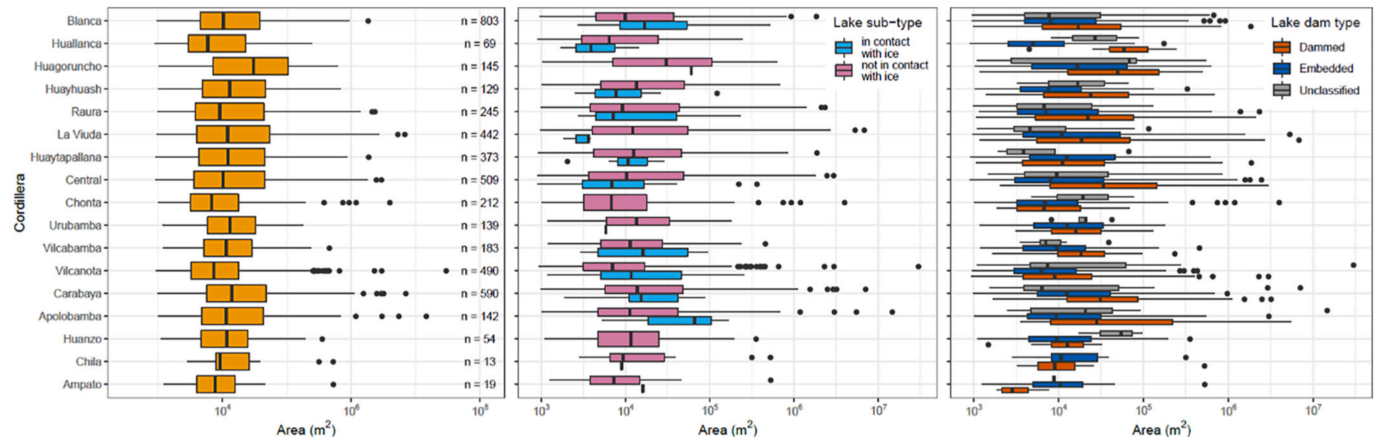

Fig. 3. Lake area for the 17 glaciated cordilleras as recorded in the projectGLOP lake inventory for (A) all lakes (number of lakes included is detailed to the right of the figure); (B) lake contact with existing glaciers (total number of lakes is 145; Table 2 and Table S6); (C) lake dam type (see also Table S7). In all plots the length of the boxes (whiskers) encompass 50% (95%) of the data, points denote outliers.

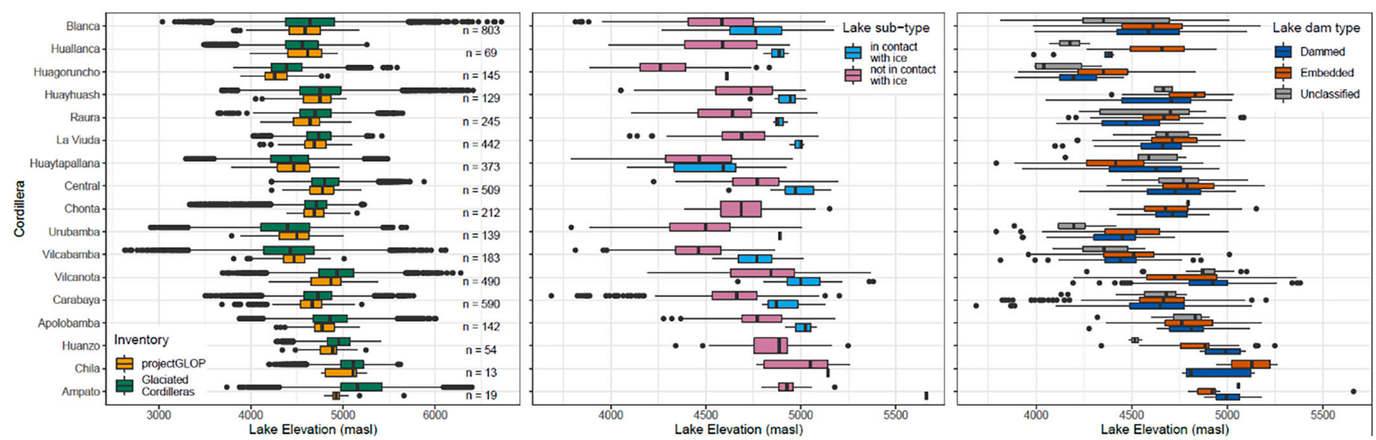

Fig. 4. Lake elevation for lakes recorded in the projectGLOP inventory for (A) all lakes, with elevation estimates for each cordillera based on a random sample of $n = 10{,}000$ points within the 3 km glacier buffer; (B) connectivity to existing glaciers (see also Table 1 and Table S8); (C) lake dam type. The length of the boxes (whiskers) encompass 50% (95%) of the data, points denote outliers.

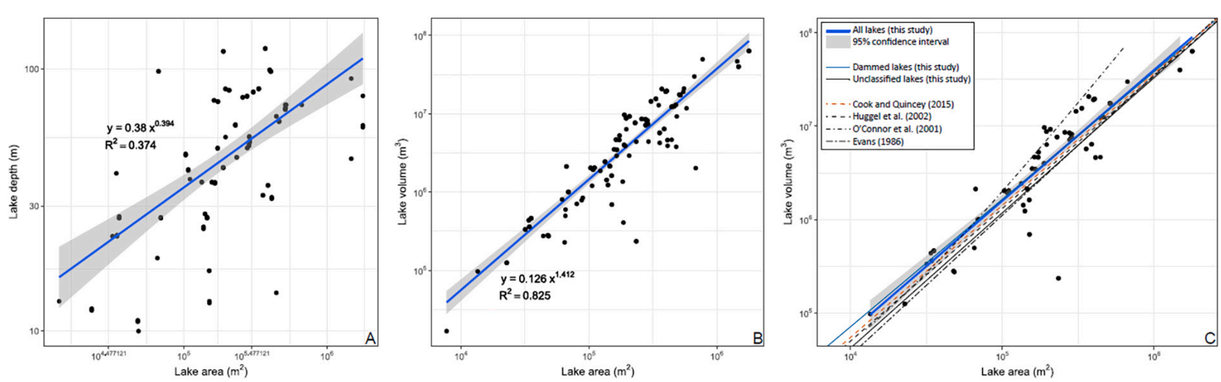

Fig. 5. Scaling relationships for lakes were derived and applied across the projectGLOP inventory to estimate lake volume using the Guardamino and Drenkhan (2016) and ANA bathymetry dataset. In all figures grey bars represent 95% confidence intervals. (A) The relationship between lake depth and area (data were available for 31 lakes with a total of 117 measurements made through time). (B) Relationship between lake area and volume (data were available for 56 lakes with 170 measurements for different time periods). (C) Comparison of the scaling relationships between lake area and lake volume for this study and for other similar studies (for specific details of the relationships presented see Table 4).

represent the most accurate and cross-comparable mapping method for long-term lake monitoring. Additionally, important metrics (Table 1), such as dam type, can only be mapped manually.

(4) The number of digitisers operating on an inventory should be limited and mapping procedures clearly communicated. To address this issue, we analysed digitised lakes from a number of different expert users for intercomparison, and produced training sites in order to reduce errors prior to lake digitisation. Our analysis of this technique

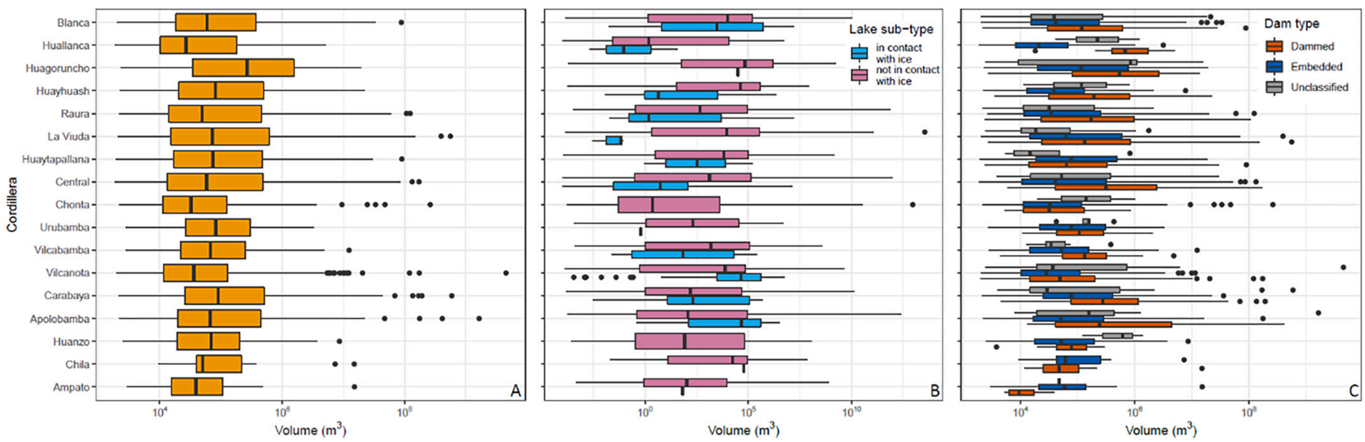

Fig. 6. Lake volume for the 17 glaciated cordilleras calculated from the scaling exponents ($V = 0.126\ A^{1.412}$) derived for all lakes (Fig. 5B and Table 4). Estimated lake volume is shown for (A) all lakes; (B) lakes depending on glacial connectivity; (C) lakes by dam type.

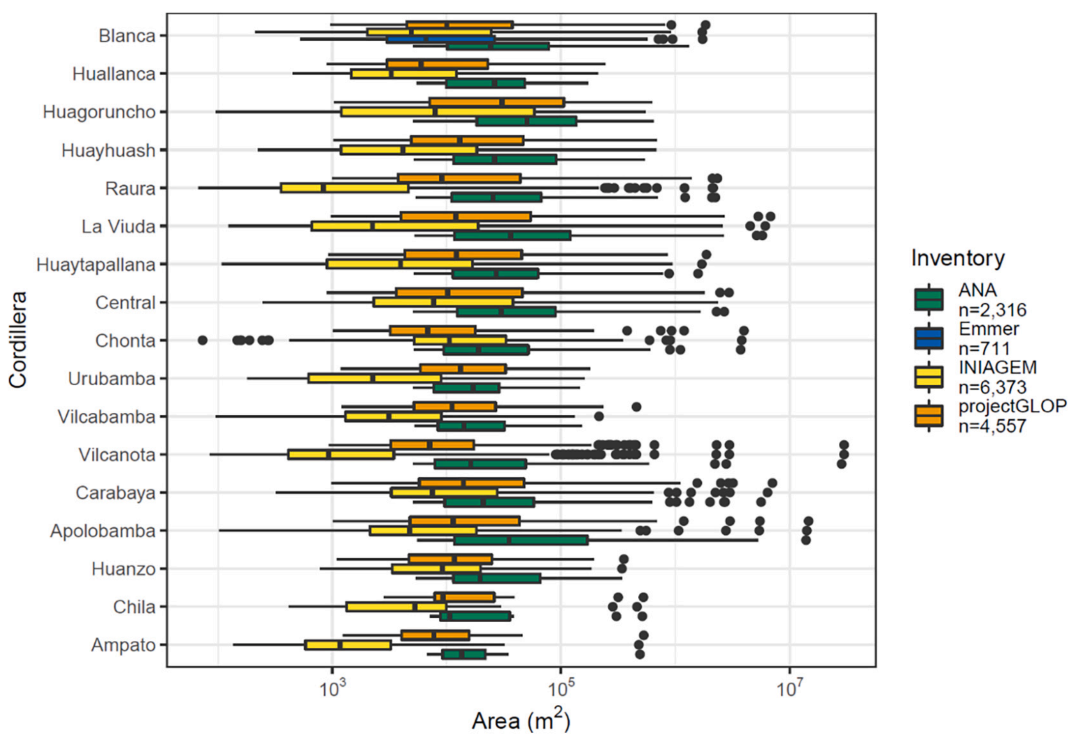

Fig. 7. Across the different inventories, pairwise comparisons using Wilcoxon rank sum tests show a significant difference in lake areas recorded (p-value <0.05 for all inventories), although this varies between cordilleras due to low numbers of lakes recorded (see Table 1 and Table 7).

highlighted the need to reduce inconsistencies in mapping between users, which is why we recommend that the number of digitisers is limited (for further information see Supplementary Information 4 Fig. S2).

3.6. Wider implications for glacial lake research

Our paper produces the most complete inventory to date of glacial lakes in the Peruvian glaciated mountains and we have provided a clear set of recommendations for the construction of similar glacier lake inventories (Section 3.3). This new inventory for Peru represents an important step towards a more complete understanding of the GLOF risk in Peru. While an assessment of the spatiotemporal GLOF pattern is beyond the scope of this paper, unpublished data (Emmer et al., in preparation) show that GLOFs only affect a small number of glacial lakes in Peru ($n = 150$ out of 4557 lakes). This is surprising given that Peru is seen as a global hotspot for GLOF events (e.g. Harrison et al., 2018), is in a region with a considerable record of damaging earthquakes and glacier detachment slides, and an area where sub-decadal climate events such as ENSO are common. Despite this, the vast majority of the lakes described and listed in this inventory have not produced GLOFs. There are several hypotheses that could be tested to explain this potential anomaly. First, the low number of GLOF-producing lakes may be due to the relatively small proportion of glacial lakes in the region dammed by unstable moraines (~28%); a consequence of factors driven by climate or debris supply. Second, it may also reflect the small percentage (~3%) of lakes that are still attached to present glaciers. This might follow from the low latitude in which the glaciers have developed, and therefore the strong response of glaciers to recent climate change (e.g. Vuille et al., 2008, 2018; Jomelli et al., 2009). This means that such lakes may still be

Table 7
The majority of cordilleras in Peru show a significant difference (p-value <0.05) in lake area between the different inventories (ANA, INAIGEM, Emmer and projectGLOP). There are only four cordilleras (Urubamba, Huanzo, Ampato and Chila) where there is no significant difference, possibly due to low lake numbers recorded (see also Table 6).

Urubamba	ANA	INAIGEM
INAIGEM	<0.01	–
projectGLOP	0.15	<0.01
Huanzo	ANA	INAIGEM
INAIGEM	<0.01	–
projectGLOP	<0.05	0.21
Ampato	ANA	INAIGEM
INAIGEM	<0.01	–
projectGLOP	0.19	<0.01
Chila	ANA	INAIGEM
INAIGEM	<0.05	–
projectGLOP	0.48	0.1

unstable and have a higher probability of failure than others; but given the small numbers of such lakes it may also suggest that the GLOF peak has passed. Third, it may be that glacier-lake systems have evolved in the region to be 'stress-hardened' to extremes such as ENSO and to earthquakes; what we are seeing now at the end of the present glacial-interglacial cycle is just the remaining lakes that have managed to survive in such an unstable environment.

Overall, the pattern of few lakes producing GLOFs may therefore highlight the likely stability of such systems to external and internal perturbations, and it calls into question the assertions from some researchers and policymakers that GLOFs will necessarily increase in frequency and magnitude in glacial mountains (see Harrison et al., 2018 for further discussion).

Finally, we now have the dataset to obtain an enhanced understanding of how glacier-lake systems evolve under conditions of climate change. While the use of such systems provides only an incomplete analogue for past deglaciation (the Peruvian Andes are tropical glacier systems which therefore provide only limited insight into other glaciated mountains which underwent deglaciation) our lake inventory will allow us to interrogate the patterns and timing of lake development.

4. Conclusions

In this paper we have presented a new glacial lake inventory for Peru which details lake distribution, extent and other important metrics, such as dam type. This dataset represents the most comprehensive inventory currently available for the Peruvian Andes. Covering an observation period between 2017 and 2019, the inventory includes 4557 glacier lakes distributed across each of the glaciated cordilleras, covering a total area of 328.86 km^2. Further analysis of these lakes revealed that the majority are now detached from current glaciers (97%) and are classified as either embedded (~67%) or (moraine) dammed (~28%) lakes, with the remaining 5% falling into the unclassified category. In terms of distribution, we found that the largest number of lakes exist in the Cordilleras Blanca and Carabaya (representing 18% and 13% of the total, respectively), whilst the Cordilleras Vilcanota and Carabaya contain the largest lake extent (representing 15% and 14% of the total, respectively). Overall, lake number, extent and type were found to vary significantly between each cordillera, which likely highlights differing topographic settings and glacier responses to recent climatic warming. Analysis of lake elevations revealed that the majority of lakes are found within a limited elevation range of between ≅ 4500 m asl and ≅ 4800 m, however, again this was shown to vary between the cordilleras. The information provided by this new inventory represents an important first step towards a better understanding of current glacial environments across the Peruvian Cordilleras.

Comparisons of the new inventory presented here with existing lake inventories available for Peru reveal a number of inconsistencies related to differences in the source imagery used and the mapping methodology applied. Such differences represent a significant challenge when attempting to monitor lake changes through time using different data sources. To address this challenge, this paper presents a robust and easily reproducible mapping methodology that facilitates the consistent recording of glacier lakes for other locations and time periods, using freely available satellite imagery (e.g. Landsat). The continual

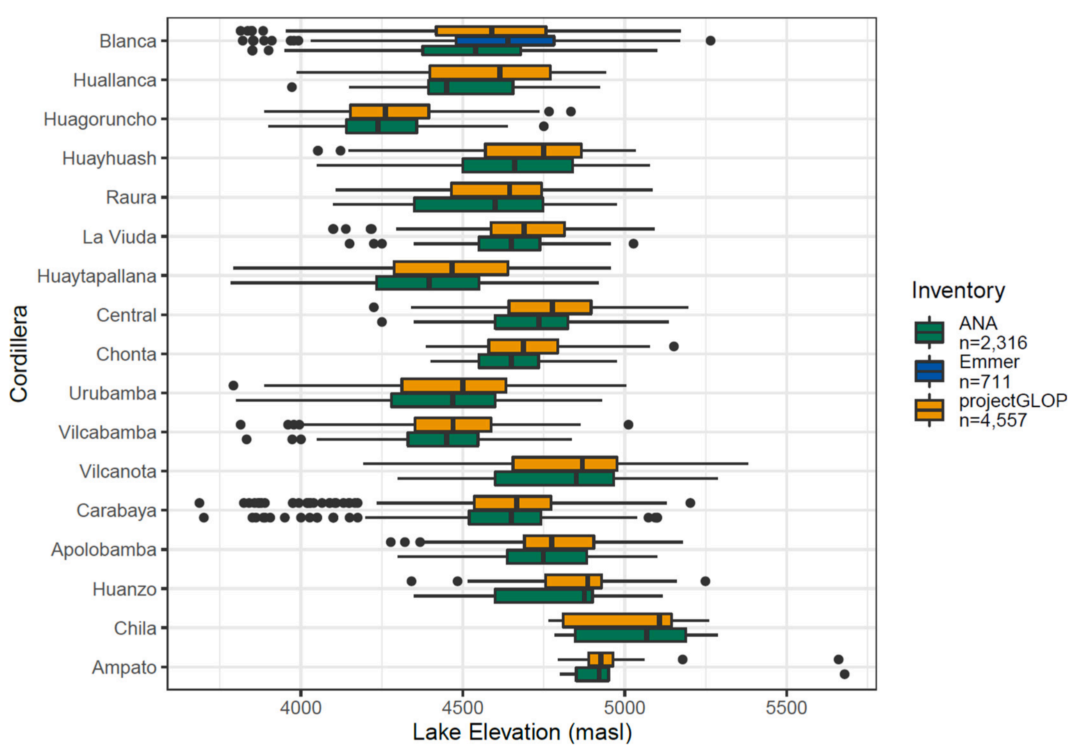

Fig. 8. The ANA and Emmer inventories both include lake elevation. Lake elevation is significantly different between the different inventories (p-value <0.05).

monitoring of glacial lakes in a standardised manner is of particular importance for the assessment of current and future risks associated with glacial hazards, such as GLOFs, which represent a significant socio-economic risk in Peru as well as in other mountainous regions globally.

Data availability

We have provided a .kml file of digitised lakes with this paper. Full details of all lakes in the inventory can be made available on request.

Declaration of Competing Interest

The authors would like to declare that there is 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.2021.103574.

References

ANA, 2014. Inventario Nacional de Glaciares y Lagunas. URL. https://hdl.handle.net/20.500.12543/199. Accessed 15/11/2020.
Baraer, M., Mark, B.G., McKenzie, J.M., Condom, T., Bury, J., Huh, K.-I., Portocarrero, C., Gómez, J., Rathay, S., 2012. Glacier recession and water resources in Peru's Cordillera Blanca. J. Glaciol. 58, 134–150.
Carrivick, J.L., Tweed, F.S., 2016. A global assessment of the societal impacts of glacier outburst floods. Glob. Planet. Chang. 144, 1–16.
Clague, J.J., Huggel, C., Korup, O., MCguire, B., 2012. Climate change and hazardous processes in high mountains. Rev. Asoc. Geol. Argent. 69 (3), 328–338.
Colonia, D., Torres, J., Haeberli, W., Schauwecker, S., Braendle, E., Giraldez, C., Cochachin, A., 2017. Compiling an inventory of glacier-bed overdeepenings and potential new lakes in de-glaciating areas of the Peruvian Andes: approach, first results, and perspectives for adaptation to climate change. Water 9 (5), 336.
Cook, S.J., Quincey, D.J., 2015. Estimating the volume of Alpine glacial lakes. Earth Surface Dynamics Discussions 3.
Davies, B.J., Glasser, N.F., 2012. Accelerating shrinkage of Patagonian glaciers from the Little Ice Age (~AD 1870) to 2011. J. Glaciol. 58 (212), 1063–1084.
Drenkhan, F., Guardamino, L., Huggel, C., Frey, H., 2018. Current and future glacier and lake assessment in the deglaciating Vilcanota-Urubamba basin, Peruvian Andes. Glob. Planet. Chang. 169, 105–118.
Dykstra, A., Owen, L., 2017. Landsat Collections — What are Tiers? URL. https://www.usgs.gov/media/videos/landsat-collections-what-are-tiers. Accessed 20/08/2020.
Emmer, A., 2018. GLOFs in the WOS: Bibliometrics, geographies and global trends of research on glacial lake outburst floods (Web of Science, 1979-2016). Nat. Hazards Earth Syst. Sci. 18 (3), 813–827.
Emmer, A., Klimeš, J., Mergili, M., Vilímek, V., Cochachin, A., 2016. 882 lakes of the Cordillera Blanca: an inventory, classification, evolution and assessment of susceptibility to outburst floods. Catena 147, 269–279.
Emmer, A., Harrison, S., Mergili, M., Allen, S., Frey, H., Huggel, C., 2020. 70 years of lake evolution and glacial lake outburst floods in the Cordillera Blanca (Peru) and implications for the future. Geomorphology 107178.
Emmer, A., Le Roy, M., Sattar, A., Veettil, B.K., Alcalá-Reygosa, J., Campos, N., Malecki, J., Cochachin, A., 2021. Glacier Retreat and Associated Processes since the Last Glacial Maximum in the Lejiamayu Valley, Peruvian Andes. J. South Am. Earth Sci. 103254.
Evans, S.G., 1986. Landslide Damming in the Cordillera of Western Canada, Seattle, Washington, 111–130, p. 1986.
GLIMS, 2019. GLIMS: Global Land Ice Measurements from Space - Monitoring the World's Changing Glaciers. URL. https://www.glims.org/. Accessed 20/05/2020.
Guardamino, L., Drenkhan, F., 2016. Evolution and potential threat of glacial lagoons in the Vilcabamba mountain range (Cusco and Apurímac, Peru) between 1991 and 2014. J. Glaciers and Mountain Ecosyst. 1 https://doi.org/10.36580/rgem.i1.21-36.
Haeberli, W., Linsbauer, A., Cochachin, A., Salazar, C., Fischer, U.H., 2016. On the morphological characteristics of overdeepenings in high-mountain glacier beds. Earth Surf. Process. Landf. 41 (13), 1980–1990.
Hanshaw, M.N., Bookhagen, B., 2014. Glacial areas, lake areas, and snow lines from 1975 to 2012: status of the Cordillera Vilcanota, including the Quelccaya Ice Cap, northern Central Andes, Peru. Cryosphere 8, 359–376.
Harrison, S., Kargel, J.S., Huggel, C., Reynolds, J., Shugar, D.H., Betts, R.A., Emmer, A., Glasser, N., Haritashya, U.K., Klimeš, J., Reinhardt, L., 2018. Climate change and the global pattern of moraine-dammed glacial lake outburst floods. Cryosphere 12 (4), 1195–1209.
Huggel, C., Kääb, A., Haeberli, W., Teysseire, P., Paul, F., 2002. Remote sensing based assessment of hazards from glacier lake outbursts: a case study in the Swiss Alps. Can. Geotech. J. 39, 316–330. https://doi.org/10.1139/t01-099.
INAIGEM, 2018. The National Inventory of Glaciers: The Glacial Mountain Ranges of Peru. URL. https://hdl.handle.net/20.500.12543/2623.
INAIGEM, 2021. Glacial Lake Inventory for Peru. Unpublished.
Jomelli, V., Favier, V., Rabatel, A., Brunstein, D., Hoffmann, G., Francou, B., 2009. Fluctuations of glaciers in the tropical Andes over the last millenium and palaeoclimatic implications: a review. Palaeogeogr. Palaeoclimatol. Palaeoecol. 281, 269–282.
Kapitsa, V., Shahgedanova, M., Machguth, H., Severskiy, I., Medeu, A., 2017. Assessment of evolution of mountain lakes and risks of glacier lake outbursts in the Djungarskiy (Jetysu) Alatau, Central Asia, using Landsat imagery and glacier bed topography modelling. Na. Hazards Earth Syst. Sci. Dis. 1–54. https://doi.org/10.5194/nhess-2017-134.
King, O., Bhattacharya, A., Bhambri, R., Bolch, T., 2019. Glacial lakes exacerbate Himalayan glacier mass loss. Sci. Rep. 9 (1), 1–9.
Kougkoulos, I., Cook, S.J., Jomelli, V., Clarke, L., Symeonakis, E., Dortch, J.M., Edwards, L.A., Merad, M., 2018. Use of multi-criteria decision analysis to identify potentially dangerous glacial lakes. Sci. Total Environ. 621, 1453–1466.
Kumar, R., Bahuguna, I.M., Ali, S.N., Singh, R., 2020. Lake inventory and evolution of glacial lakes in the Nubra-Shyok basin of Karakoram Range. Earth Systems and Environ. 4 (1), 57–70.
Loriaux, T., Casassa, G., 2013. Evolution of glacial lakes from the Northern Patagonia Icefield and terrestrial water storage in a sea-level rise context. Glob. Planet. Chang. 102, 33–40.
Mahdianpari, M., Salehi, B., Mohammadimanesh, F., Homayouni, S., Gill, E., 2019. The first wetland inventory map of newfoundland at a spatial resolution of 10 m using sentinel-1 and sentinel-2 data on the google earth engine cloud computing platform. Remote Sens. 11 (1), 43. https://doi.org/10.3390/rs11010043.
Masiokas, M., Rivera, A., Espizua, L.E., Villalba, R., Delgado, S., Aravena, J.C., 2009. Glacier fluctuations in extratropical South America during the past 1000 years. Palaeogeogr. Palaeoclimatol. Palaeoecol. 281, 242–268.
McKillop, R.J., Clague, J.J., 2007. A procedure for making objective preliminary assessments of outburst flood hazard from moraine-dammed lakes in southwestern British Columbia. Nat. Hazards 41, 131–157.
Mosquera, P.V., Hampel, H., Vázquez, R.F., Alonso, M., Catalan, J., 2017. Abundance and morphometry changes across the high-mountain lake-size gradient in the tropical Andes of Southern Ecuador. Water Resour. Res. 53 (8), 7269–7280.
Muñoz, R., Huggel, C., Frey, H., Cochachin, A., Haeberli, W., 2020. Glacial lake depth and volume estimation based on a large bathymetric dataset from the Cordillera Blanca, Peru. Earth Surf. Process. Landf. https://doi.org/10.1002/esp.4826.
NextGIS, 2015. QuickMapServices: Easy Basemaps in QGIS. URL. https://nextgis.com/blog/quickmapservices/.
O'Connor, J.E., Hardison III, J.H., Costa, J.E., 2001. Debris Flows from Failures of Neoglacial-Age Moraine Dams in the Three Sisters and Mount Jeerson Wilderness Areas, Oregon. US Geological Survey Professional Paper 1606, Reston, Virginia, p. 105.
Quincey, D.J., Richardson, S.D., Luckman, A., Lucas, R.M., Reynolds, J.M., Hambrey, M. J., Glasser, N.F., 2007. Early recognition of glacial lake hazards in the Himalaya using remote sensing datasets. Glob. Planet. Chang. 56 (1–2), 137–152.
Rabatel, A., Francou, B., Soruco, Á., Gomez, J., Cáceres, B., Ceballos, J.L., Basantes, R., Vuille, M., Sicart, J.E., Huggel, C., Scheel, M., 2013. Current state of glaciers in the tropical Andes: a multi-century perspective on glacier evolution and climate change. Cryosphere 7 (1), 81–102.
Raup, B.H., Racoviteanu, A., Khalsa, S.J.S., Helm, C., Armstrong, R., Arnaud, Y., 2007. The GLIMS Geospatial Glacier Database: a New Tool for Studying Glacier Change. Glob. Planet. Chang. 56, 101–110. https://doi.org/10.1016/j.gloplacha.2006.07.018.
Reynolds, J.M., 1992. The identification and mitigation of glacier-related hazards: Examples from the Cordillera Blanca, Peru. In: McCall, G.J.H., Laming, D.C.J., Scott, S. (Eds.), Geohazards. Chapman & Hall, London, pp. 143–157.
Reynolds, J.M., 2014. Assessing glacial hazards for hydro development in the Himalayas, Hindu Kush and Karakorum. In. J. Hydropower Dams 2, 60–65.
Richardson, S.D., Reynolds, J.M., 2000. An overview of glacial hazards in the Himalayas. Quat. Int. 65, 31–47.
Shugar, D.H., Burr, A., Haritashya, U.K., Kargel, J.S., Watson, C.S., Kennedy, M.C., Bevington, A.R., Betts, R.A., Harrison, S., Strattman, K., 2020. Rapid worldwide growth of glacial lakes since 1990. Nat. Clim. Chang. https://doi.org/10.1038/s41558-020-0855-4.
UGRH: Inventario de glaciares del Peru, 2014. URL. http://groundwater.sdsu.edu/INVENTARIO_GLACIARES_ANA.pdf. Accessed 02/11/2020.
UNEP, 2007. Global Outlook for Ice and Snow, UNEP, p. 235. URL. http://hdl.handle.net/20.500.11822/7792. Accessed 15/11/2020.

Verpoorter, C., Kutser, T., Seekell, D.A., Tranvik, L.J., 2014. A global inventory of lakes based on high-resolution satellite imagery. Geophys. Res. Lett. 41 (18) https://doi.org/10.1002/2014GL060641.
Viani, C., Giardino, M., Huggel, C., Perotti, L., Mortara, G., 2016. An overview of glacier lakes in the Western Italian Alps from 1927 to 2014 based on multiple data sources (historical maps, orthophotos and reports of the glaciological surveys). Geogr. Fis. Din. Quat. 39 (2), 203–214.
Vilímek, V., Klimeš, J., Červená, L., 2016. Glacier-related landforms and glacial lakes in Huascarán National Park, Peru. J. Maps 12 (1), 193–202.
Vuille, M., Francou, B., Wagnon, P., Juen, I., Kaser, G., Mark, B.G., Bradley, R.S., 2008. Climate change and tropical Andean glaciers: past, present and future. Earth Sci. Rev. 89 (3–4), 79–96.
Vuille, M., Carey, M., Huggel, C., Buytaert, W., Rabatel, A., Jacobsen, D., Soruco, A., Villacis, M., Yarleque, C., Timm, O.E., Condom, T., Salzmann, N., Sicart, J.-E., 2018. Rapid decline of snow and ice in the tropical Andes - Impacts, uncertainties and challenges ahead. Earth Sci. Rev. 176, 195–213.
Wang, X., Liu, S., Ding, Y., Guo, W., Jiang, Z., Lin, J., Han, Y., 2012. An approach for estimating the breach probabilities of moraine-dammed lakes in the Chinese Himalayas using remote-sensing data. Nat. Hazards Earth Syst. Sci. 12, 3109–3122. https://doi.org/10.5194/nhess-12-3109-2012.
Wang, X., Guo, X., Yang, C., Liu, Q., Wei, J., Zhang, Y., Liu, S., Zhang, Y., Jiang, Z., Tang, Z., 2020. Glacial lake inventory of High Mountain Asia (1990–2018) derived from Landsat images. Earth System Science Data Discussions 1–23.
WGMS, 2021. Glacier Monitoring: Peru. URL. https://wgms.ch/downloads/cp/cp_Peru.pdf. Accessed 15/11/2020.
Wilson, R., Glasser, N.F., Reynolds, J.M., Harrison, S., Anacona, P.I., Schaefer, M., Shannon, S., 2018. Glacial lakes of the Central and Patagonian Andes. Glob. Planet. Chang. 162, 275–291.
Worni, R., Huggel, C., Stoffel, M., 2013. Glacial lakes in the Indian Himalayas—from an area-wide glacial lake inventory to on-site and modeling based risk assessment of critical glacial lakes. Sci. Total Environ. 468, S71–S84.