Mapping glacier lakes in Peru

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Abstract: One consequence of current and likely future melting of high mountain glaciers is the development of glacial lakes. Their evolution over time has implications for future water supplies in arid mountains and for the timing and magnitude of glacier hazards, such as Glacial Lake Outburst Floods (GLOFs).

GLOF initiation depends on how lakes are connected to the glacial system, resulting from myriad processes such as the destabilisation of moraine dams and glacier front calving. To better understand these processes, we have undertaken an inventory of all glacier lakes in the Peruvian Cordillera Blanca (CB) for 2019. We used manual digitisation from Landsat RGB at 30m resolution and have recorded the type of lake dam and its connection with surrounding glaciers and mountain slopes. We have also obtained lake inventories from INIAGEM (Instituto Nacional de Investigación en Glaciares y Ecosistemas de Montaña; 2016) and ANA (Autoridad Nacional del Agua; 2018) Here we compare these different inventories and discuss both the methods and effectiveness of each for understanding GLOF hazards in the Peruvian Andes.

1. Introduction

The Cordillera Blanca has seen significant glacial recession since the end of the Little Ice Age, resulting in numerous glacial lakes in the region. There have been several catastrophic outburst flood (GLOF) events during the 20th Century. Understanding lake abundance and size is important for understanding current GLOF risk. Here we present a new manually digitised inventory (projectGLOP, 2019; Fig. 1) and compare this with existing lake inventories (ANA, 2014; INIAGEM, 2016).

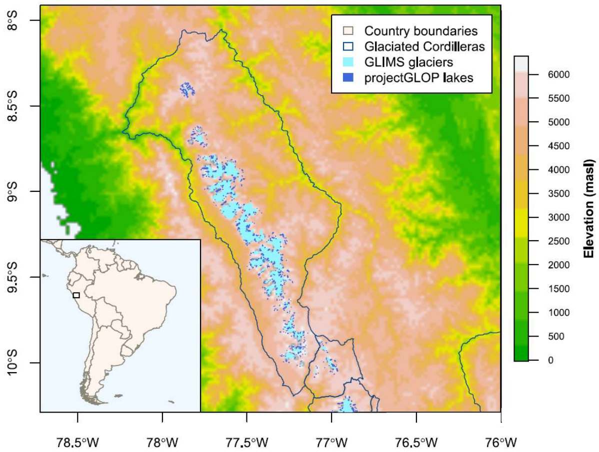

Fig. 1 Cordillera Blanca study site. The location of current glaciers (GLIMS, 2019) are shown. Lakes recorded occur within LIA limits (~3km from existing glaciers). The insert map shows the location of the CB in Peru.

2. Methods

Google Earth Engine (GEE) was used to obtain cloudless (<5% cover) Landsat images (30m Landsat RGB, 15m Landsat Panchromatic). Manual digitization of lakes was undertaken for the CB for 2019 in QGIS. High resolution Bing Satellite, ESRI and Google Hybrid data (QGIS QuickMapServices, Fig. 2a) were used to help with lake detection and identification of the dam type. Data recorded included dam type, elevation, lake area and connectivity to the glacial system.

Elevation (30m SRTM data) were sampled into the different inventories for comparison. Area was calculated in QGIS by reprojecting all datasets into UTM zone 18 S (EPSG: 5387). These data were then analysed and plotted in R-Studio.

Several other metrics, including aspect, connectivity to the glacial system and evidence for past GLOFs were also recorded in the inventory, but are not presented here.

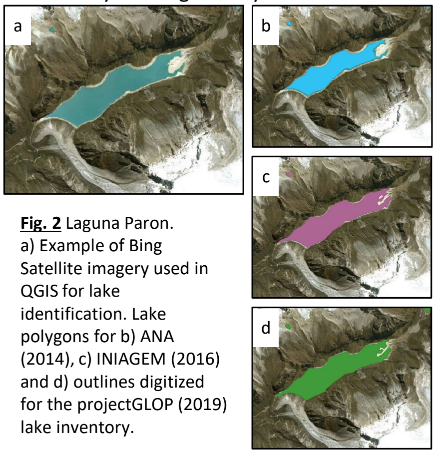

Fig. 2 Laguna Paron. a) Example of Bing Satellite imagery used in QGIS for lake identification. Lake polygons for b) ANA (2014), c) INIAGEM (2016) and d) outlines digitized for the projectGLOP (2019) lake inventory.

3. Results

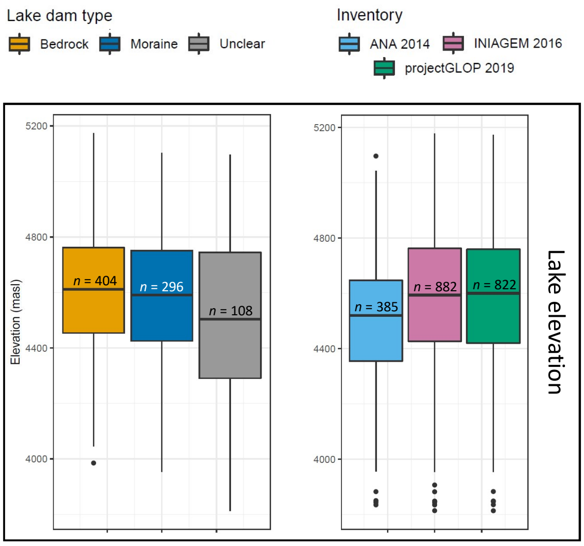

Fig. 3 (left) Boxplot showing the elevation distribution for projectGLOP (2019) lakes in the CB according to dam type. (right) Boxplot of elevation for the three different inventories. Number of lakes (*n*) is included on each boxplot (see Tab. 1).

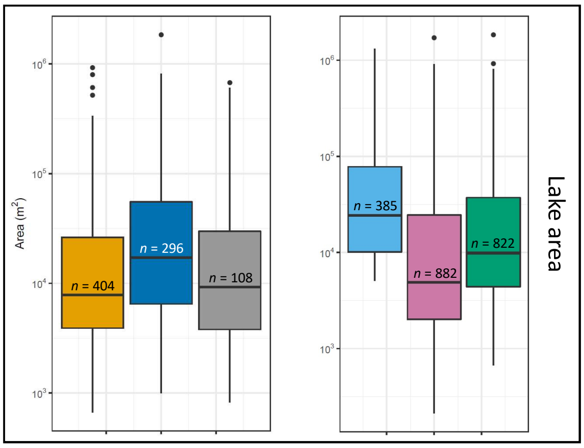

Fig. 4 (left) Boxplot showing lake area recorded for lakes in the projectGLOP (2019) inventory for the CB according to dam type (see Tab. 2). (right) Boxplot showing the distribution of lakes areas calculated for each of the different inventories. Number of lakes (*n*) is included on each boxplot.

Lake elevation: For the CB, 822 lakes were recorded in the projectGLOP (2019) inventory. These are predominantly bedrock (*n* = 404) and moraine dammed (*n* = 296) (Fig. 3); we were unable to determine the dam type for 108 lakes, and one lake (not included here) was landslide dammed. A pairwise Wilcox test showed a significant difference ($p < 0.05$) between elevations recorded for bedrock dammed lakes and unclear lakes, but there was no difference between bedrock and moraine dammed lakes.

Between the different inventories, ANA (2014) consistently records lakes at lower elevations, while INIAGEM (2016) and projectGLOP (2019) are statistically similar (Tab. 1).

Tab. 1 The results of a pairwise Wilcox test comparing elevation distributions between inventories.

	ANA (2014)	INIAGEM (2016)
INIAGEM (2016)	$p < 0.01$	-
projectGLOP (2019)	$p < 0.01$	$p = 0.95$

Lake area: For lakes recorded in the projectGLOP (2019) inventory, there is a significant difference in lake area between the different dam types (Tab. 2). Mapping resolution has an impact on lake numbers recorded and subsequent size distributions (Fig. 4); the INIAGEM (2016) dataset uses higher resolution imagery to record lakes in the CB that the others; shown in the lower recorded lake areas. A pairwise Wilcox test showed a significant difference between all lake inventories.

Tab. 2 The results of the pairwise Wilcox test comparing lake area for different lake dam types in the projectGLOP (2019) inventory.

	Bedrock	Moraine
Moraine	$p < 0.01$	-
Unclear	$p = 0.59$	$p < 0.01$

4. Conclusions

Differences in mapping resolution has an impact on lake inventory statistics. projectGLOP mapping lies (statistically) between the ANA (2014) and INIAGEM (2016) datasets. 30m Landsat datasets provide opportunities for lake evolution (time series) analysis. Manual mapping is time-intensive, but provides opportunities to include important metrics (e.g. dam type), vital for understanding changing GLOF risk.