What's in a lake?

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CR1.5 - '*Glaciation and climate change in the Andean Cordillera*': EGU21-12241

EGU General Assembly 2021

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A. Overview

- **Climate change** is resulting in **mass loss** and the **retreat** of glaciers in the Andes, exposing steep valley sides, over-deepened valley bottoms, and creating **glacial lakes**.
- Glacial Lake Outburst Floods (GLOFs) have presented the biggest **risk** posed by glacier recession in Peru.
- **Understanding the characteristics** of lakes that have failed in the past will provide an aid to identifying those lakes that **might fail in the future** and narrow down which lakes are of greatest interest for reducing the risks to local vulnerable populations.
- Using a **newly created lake inventory** for the Peruvian Andes (Wood *et al.*, in review) and a **comprehensive GLOF inventory** (Emmer *et al.*, EGU21-9744) we investigate lakes from which GLOFs have occurred in the past.
- This is to establish which **physical components** of the **glacial lake systems** are common to those lakes that have failed previously and which can be identified **remotely, easily and objectively**, in order to **improve** existing methods of **hazard assessment**.

CLIMATE CHANGE

Air temperature | **Precipitation change** | **Intensified weather systems**

→ Change in **frequency & magnitude** of montane/glacial hazards

→ Impact on **socio-economic** activities

→ Continual **monitoring/ risk assessment** & where possible **remediation**

Examples of (left) moraine dammed and (right) **embedded** bedrock dammed lake in the Cordillera Blanca, Peru

University of Exeter, Prifysgol Aberystwyth University, University of Huddersfield, Reynolds International, University of Graz, University of Dundee, INAIGEM, UNASAM, CONCYTEC, NERC Science of the Environment, Newton-Paulet Fund

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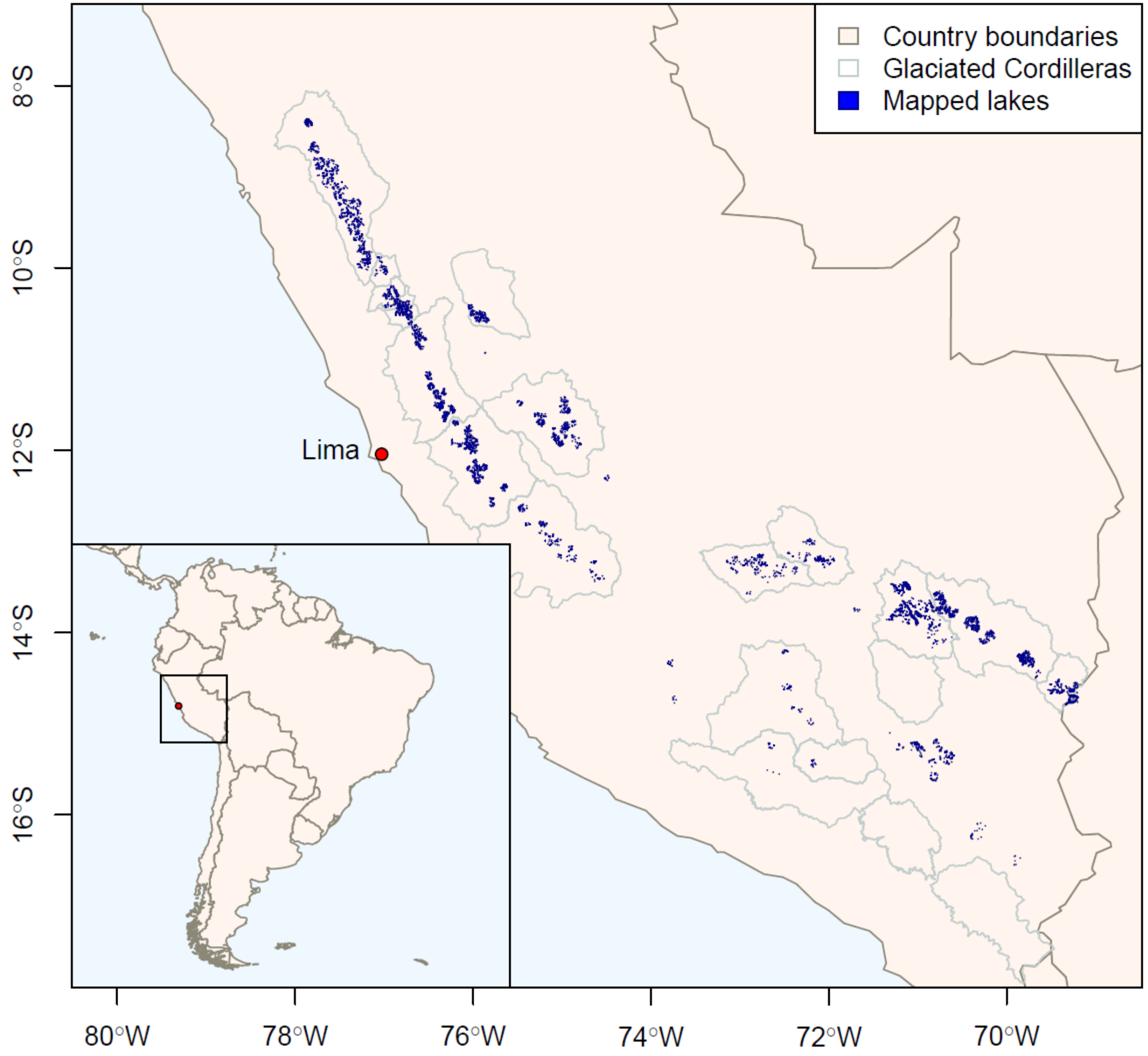
B. Glacier lake inventory for Peru

(Wood *et al.*, in review)

- A new glacier lake inventory was created for the Peruvian Cordilleras
- Manual digitization of **4,557 glacial lakes** covering a total area of 328,85 km^2
- Inventory includes **important metrics** (e.g. dam type and volume)
- Conducted pilot **temporal analysis** (Landsat 1984-2019)

- Results show
  - **97%** are **detached from existing glaciers**:
  - Embedded ~64%
  - Moraine dammed ~27%
  - Lake size varies with dam type

- Important first step towards:
  - (1) bettering our **understanding** of **current glacial environments** in Peru
  - (2) assessing **risks** associated with **GLOFs**



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A. Overview
B. Lakes and GLOFs
C. GLOF hazards
D. Results
E. Summary

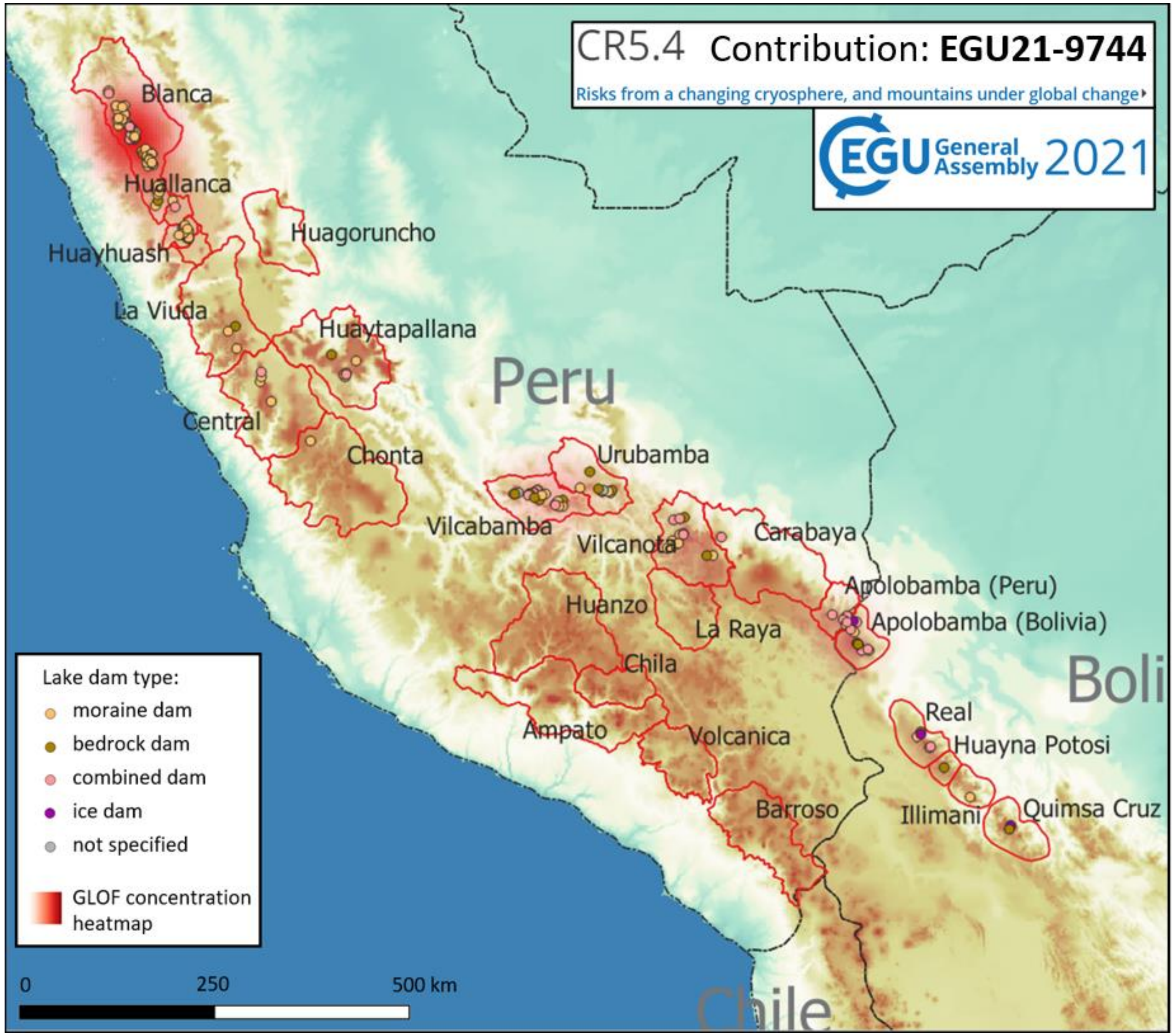
B. GLOF inventory for Peru

(Emmer, A. *et al.*, EGU21-9744)

- New GLOF inventory for Peru
- **158 GLOF events** from 150 lakes across Peru (and Bolivia)
- 66% previously unrecorded

- Results show:
  - ~60% are from moraine dammed lakes
  - ~18% are from lakes with combined dams
  - ~16% originate from embedded lakes
  - Cordilleras Blanca, Huayhuash and Vilcabamba are GLOF hotspots

- Inventories important for GLOF hazard assessments to **characterise** lakes which pose a **potential hazard**



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A. Overview

B. Lakes and GLOFs

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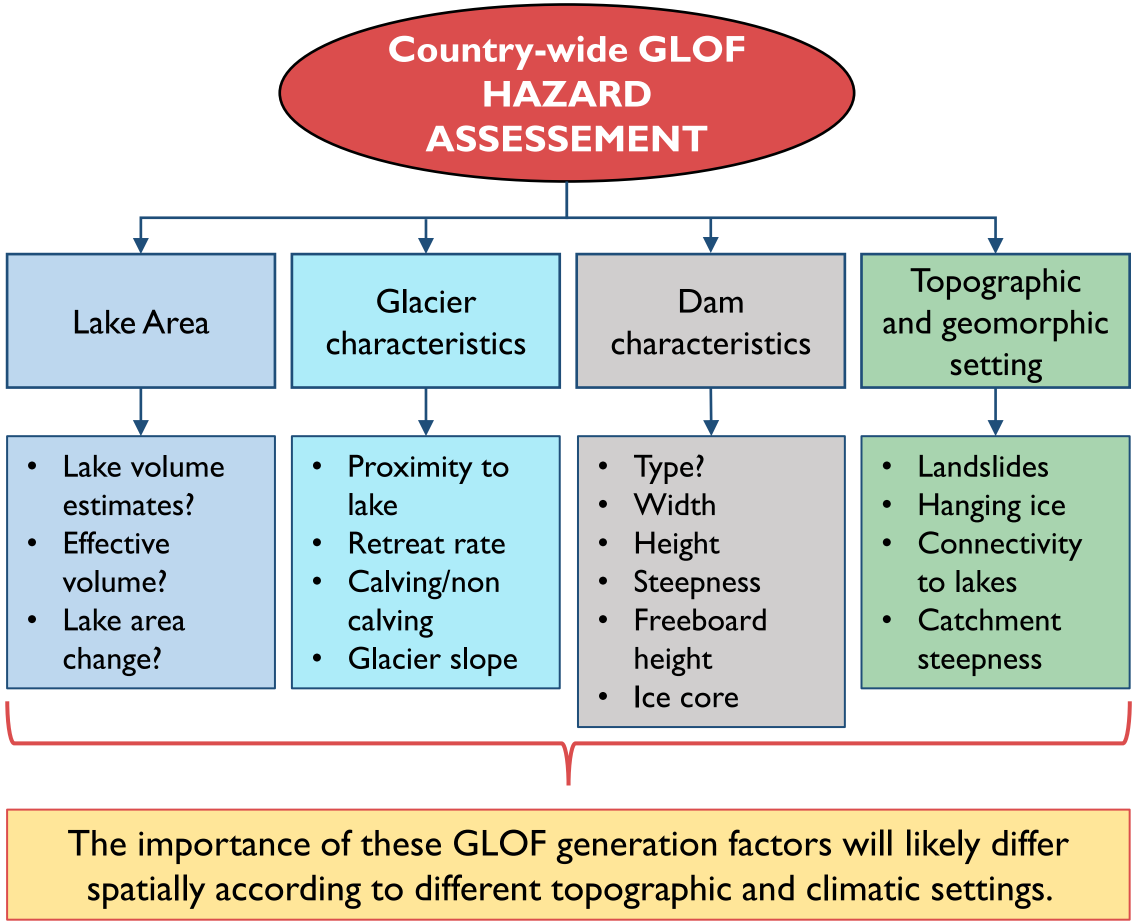
E. Summary

C. GLOF hazard assessment

- Past research has used a **multi-criteria approach** to produce **GLOF hazard assessments** (e.g. Kougkoulos *et al.*, 2018; Allen *et al.*, 2019; Annacona *et al.*, 2014; Khadka *et al.*, 2021; Islam & Patel, 2020).
- These criteria are usually **weighted** according to relative importance for determining **GLOF** thresholds and trigger parameters.
- For the **weighting** procedure to be done in a meaningful manner, it ideally needs to be **informed** by **past GLOF events** in the study region.
- Historical records of **past GLOF events** are often sparse but can be added to through analysis of **satellite imagery**; for example, the presence of distinctive v-shaped troughs in adjacent terminal moraines and debris fans can indicate past events.



(Above) Showing the key components and metrics for consideration in a country-wide GLOF hazard assessment

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A. Overview

B. Lakes and GLOFs

C. GLOF hazards

D. Results

E. Summary

Lake Area

Lake volume estimates?

Effective volume?

Area change?

Dam characteristics

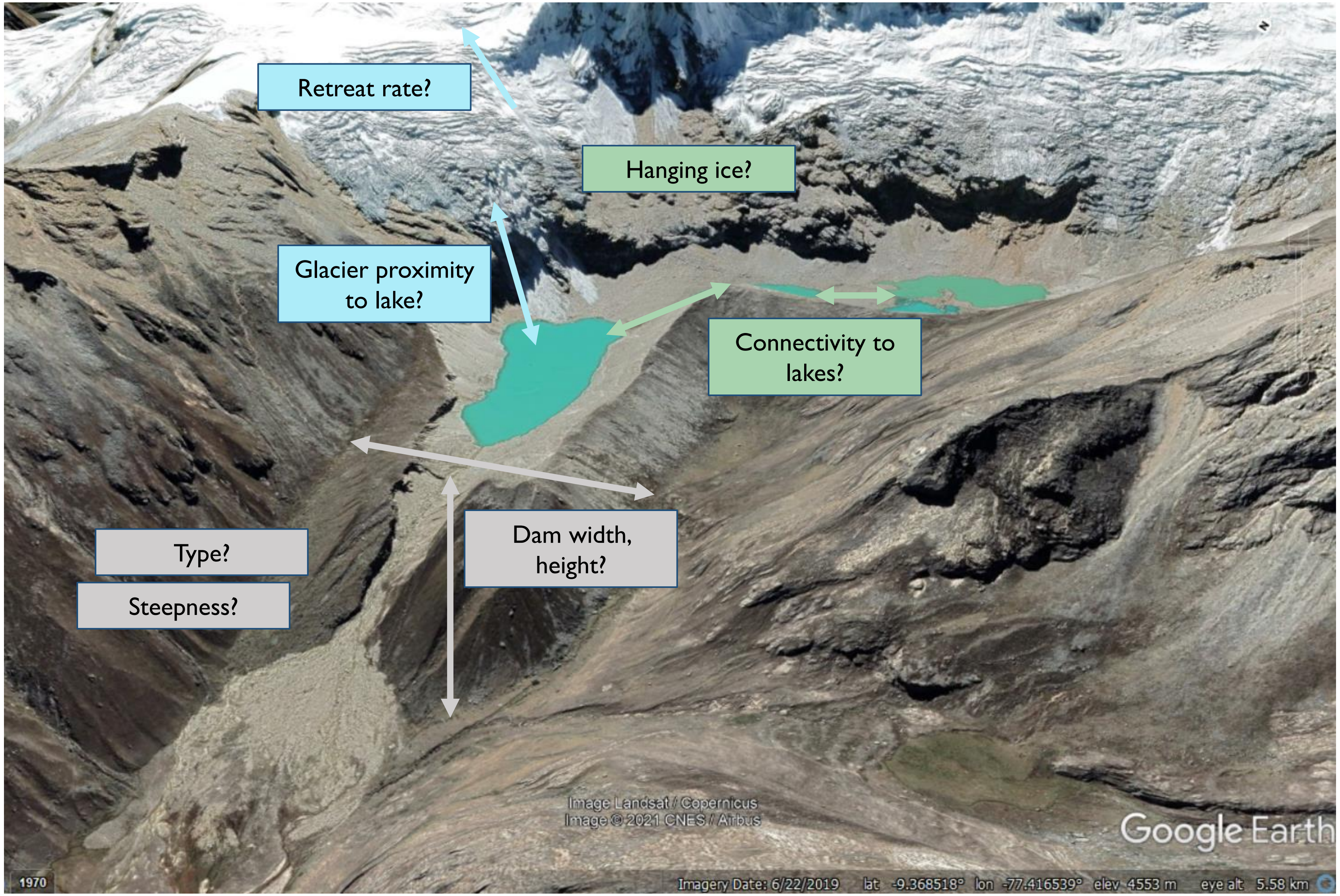
Type?

Dam width, height?

Steepness?

Freeboard height?

Ice core?



Glacier characteristics

Calving/non calving?

Glacier slope?

Retreat rate?

Glacier proximity to lake?

Topographic and geomorphic setting

Landslides?

Hanging ice?

Connectivity to lakes?

Catchment steepness?

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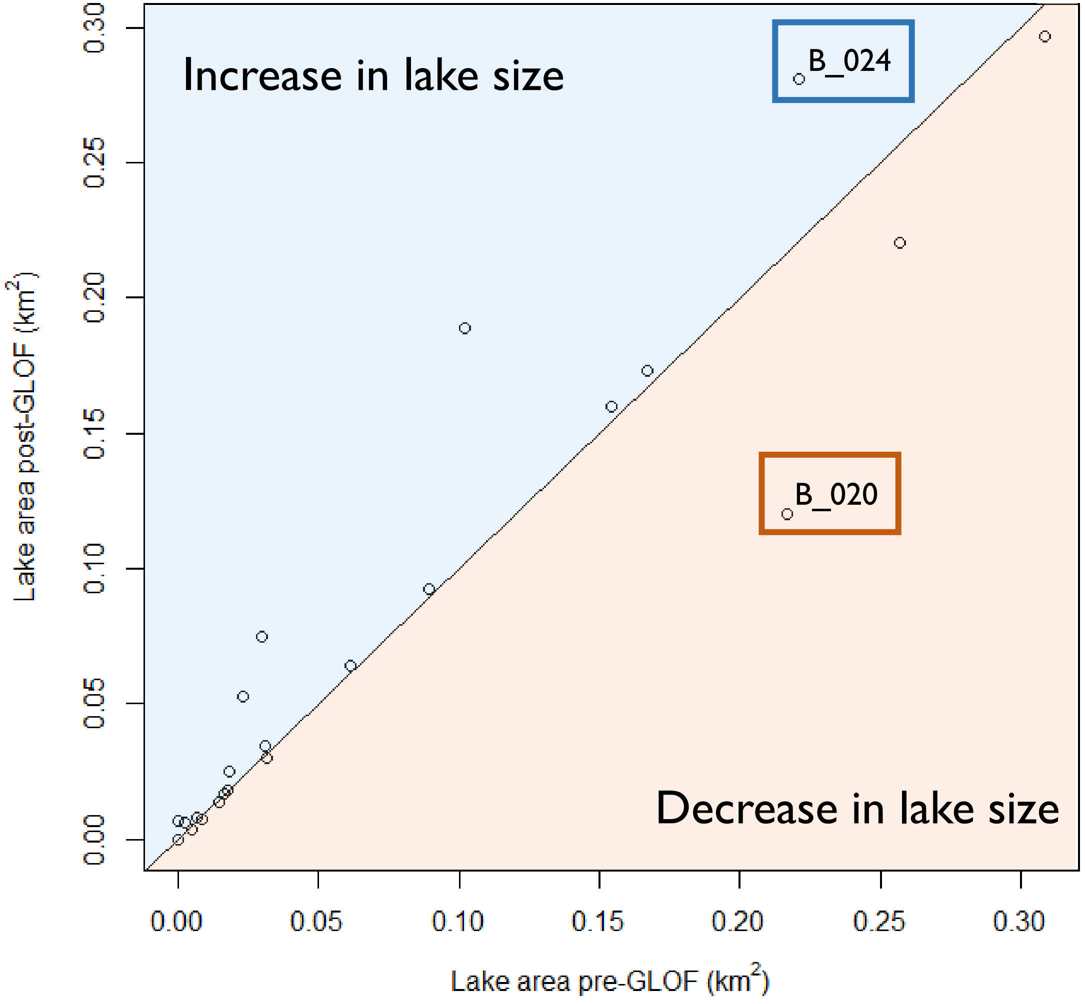
D. Results: Lake area change

- For 26 GLOF events between 1984-2019 lake area change was detected automatically (using Landsat)
- For the majority of lakes, **lake area increased** between the year prior to the GLOF event and the following year, whereas in few cases we see an expected **reduction in lake area**

- **GLOF B_020**
  - Location: Huaytapallana
  - Timing: Aug 1990 to Feb 1991
  - Dam type: Moraine
  - Glacier contact: No
  - Elevation: 4640 m a.s.l.

- **GLOF B_024**
  - Location: Huayhuash
  - Timing: Jan 1999
  - Dam type: Moraine
  - Glacier contact: Recent
  - Elevation: 4233 m a.s.l.



(Above) showing the change in lake size for Landsat images pre-GLOF event (year – 1) and post-GLOF (year + 1) for 26 lakes across Peru.

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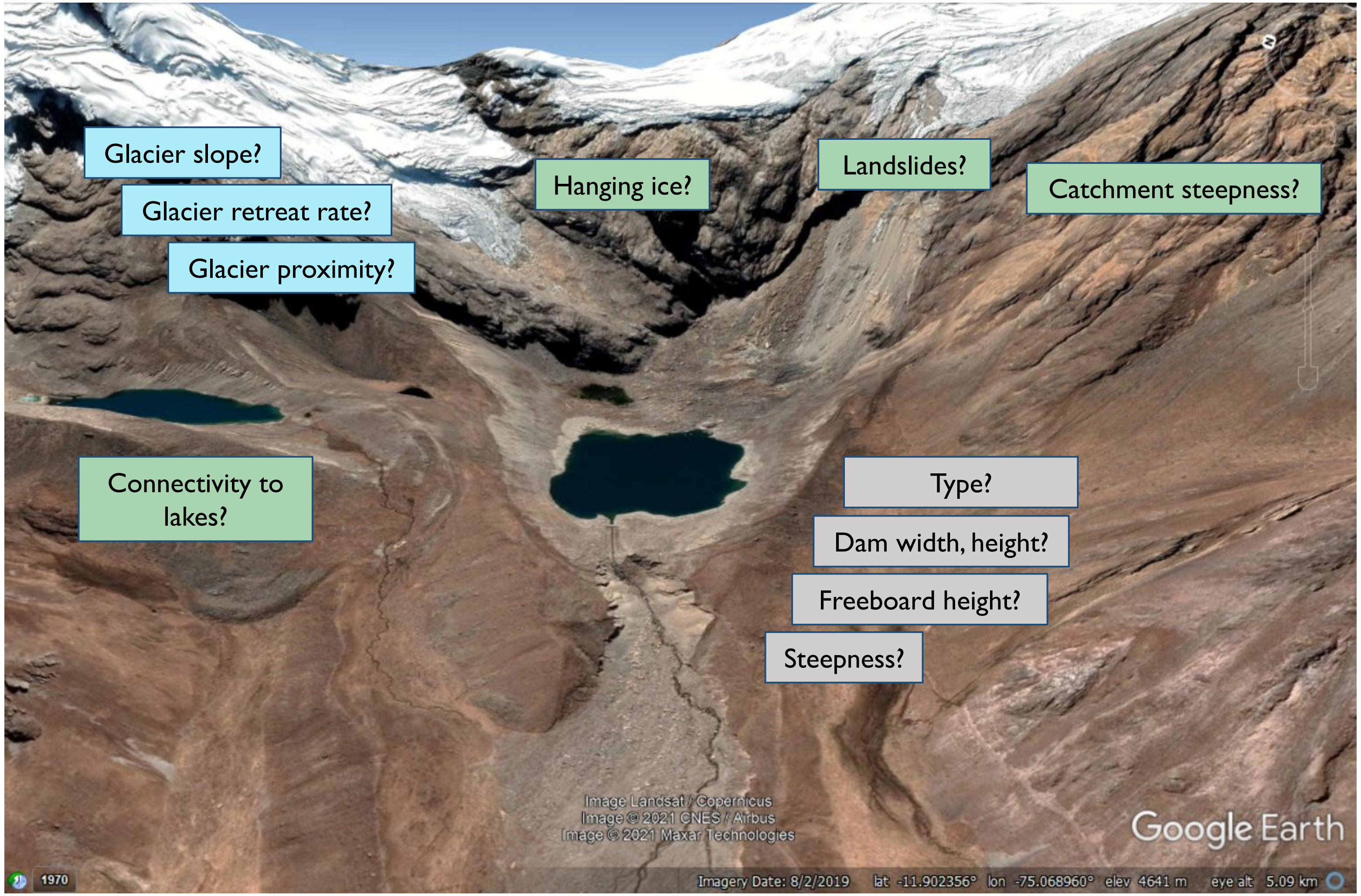
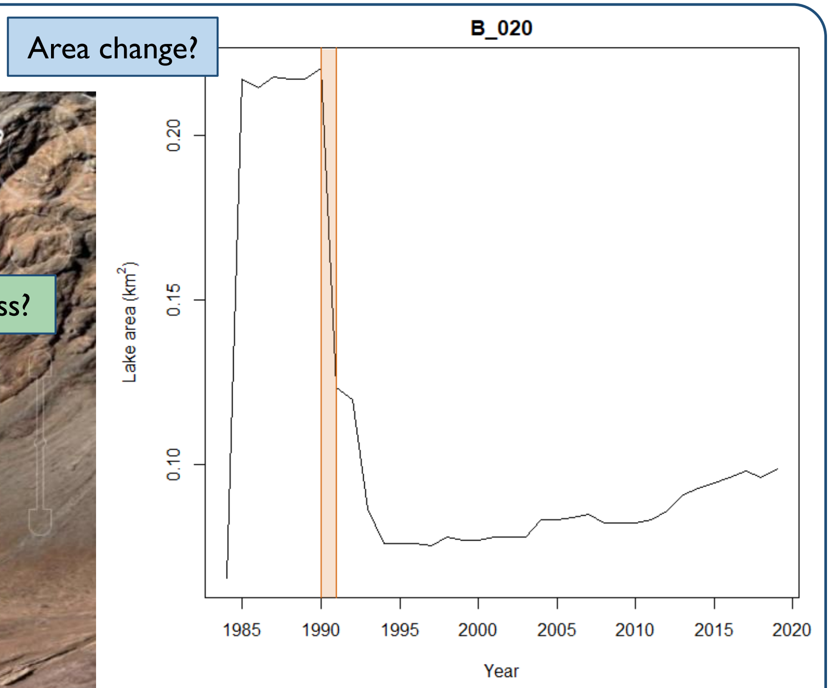
D. Results: Lake area change for GLOF B_020





(Above) Showing lake area change though time based on Landsat imagery. **Vertical lines** indicate approximate GLOF timing. GLOF event coincides with a drastic reduction of lake area.

(Left) Google Earth view of the lake in 2019. Clear damage and breach of the frontal moraine can be seen. Lake is flanked by steep slopes to the east and lateral/terminal moraines to the north, west and south.

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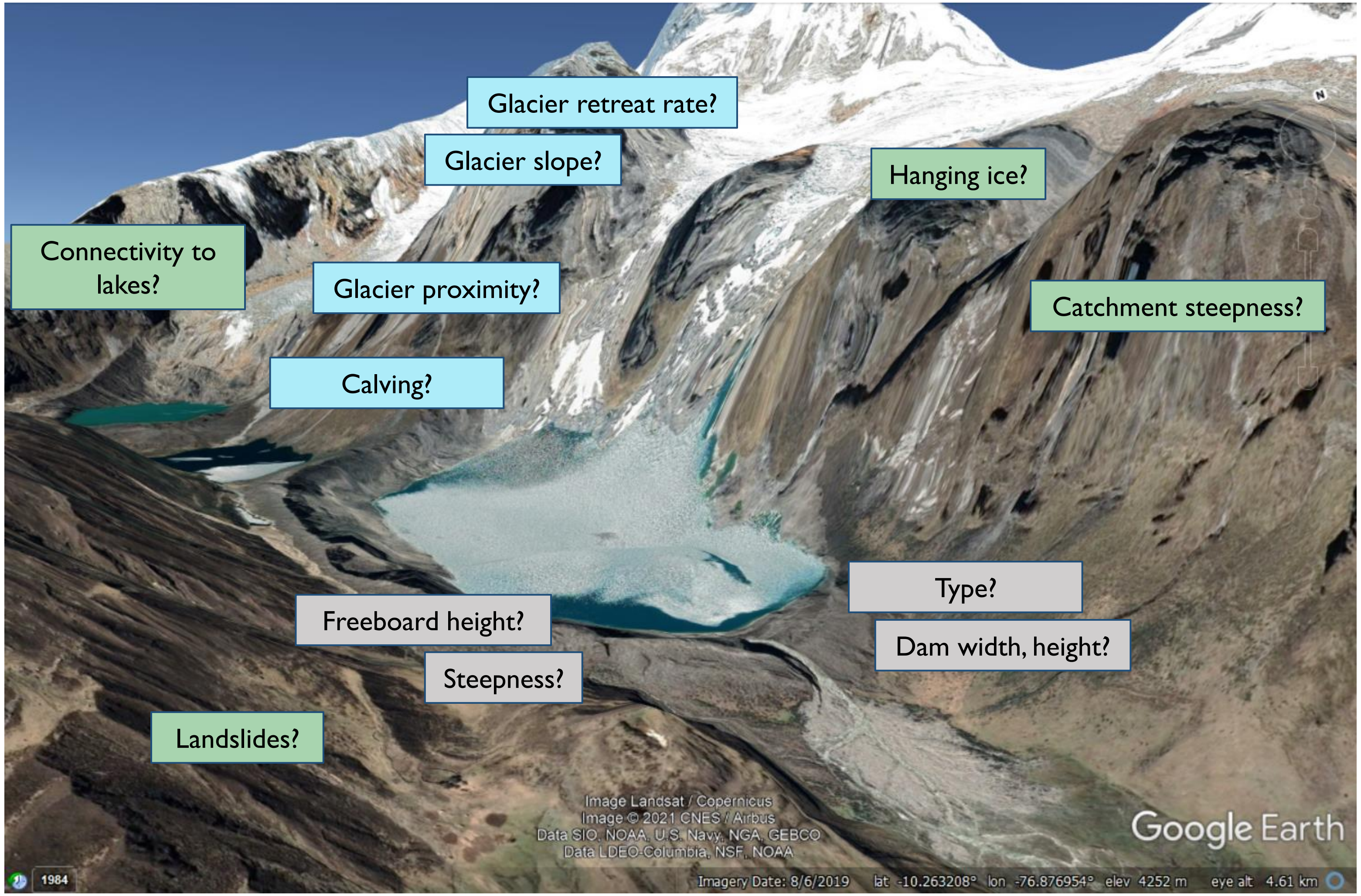
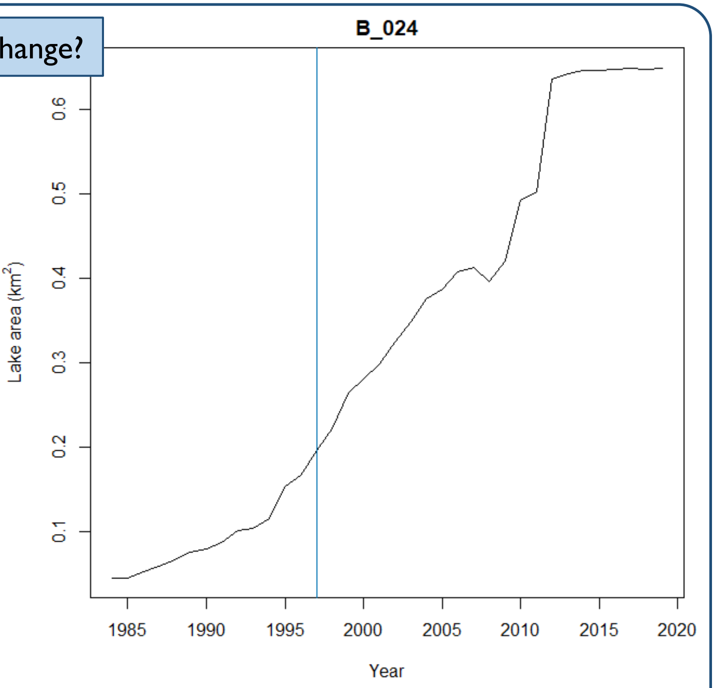
D. Results: Lake area change for GLOF B_024



Area change?



(Above) Showing lake area change though time based on Landsat imagery. **Vertical line** indicates GLOF timing. GLOF event does not result in a reduction of lake area as might be expected.

(Left) Google Earth view of the lake in 2019. Clear damage and breach of the frontal moraine can be seen. Lake is flanked by steep slopes to the west and lateral moraines to the east and north.

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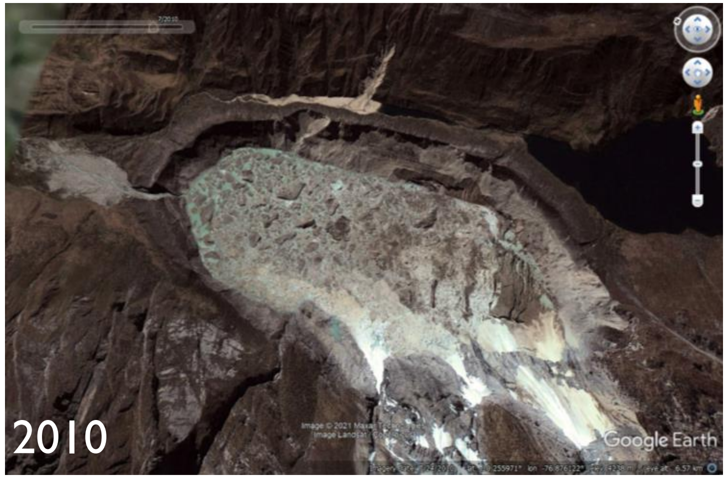
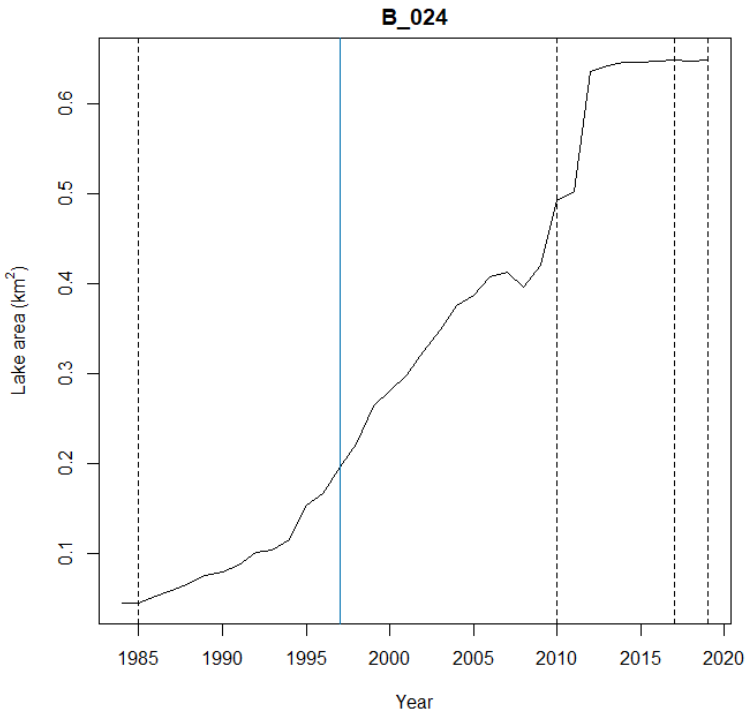
D. Results: Lake area change for GLOF B_024

(Below) Ice cover in early images (1985 and 2010) may obscure true lake extent. 1985 image suggests close proximity to glacier.





(Above) Showing lake area change though time based on Landsat imagery. **Vertical line** indicates GLOF timing, **dashed lines** indicate timing of the surrounding Google Earth images.

(Below) Little change in lake size between 2017-2019 (indicated in the Google Earth images and center graph).

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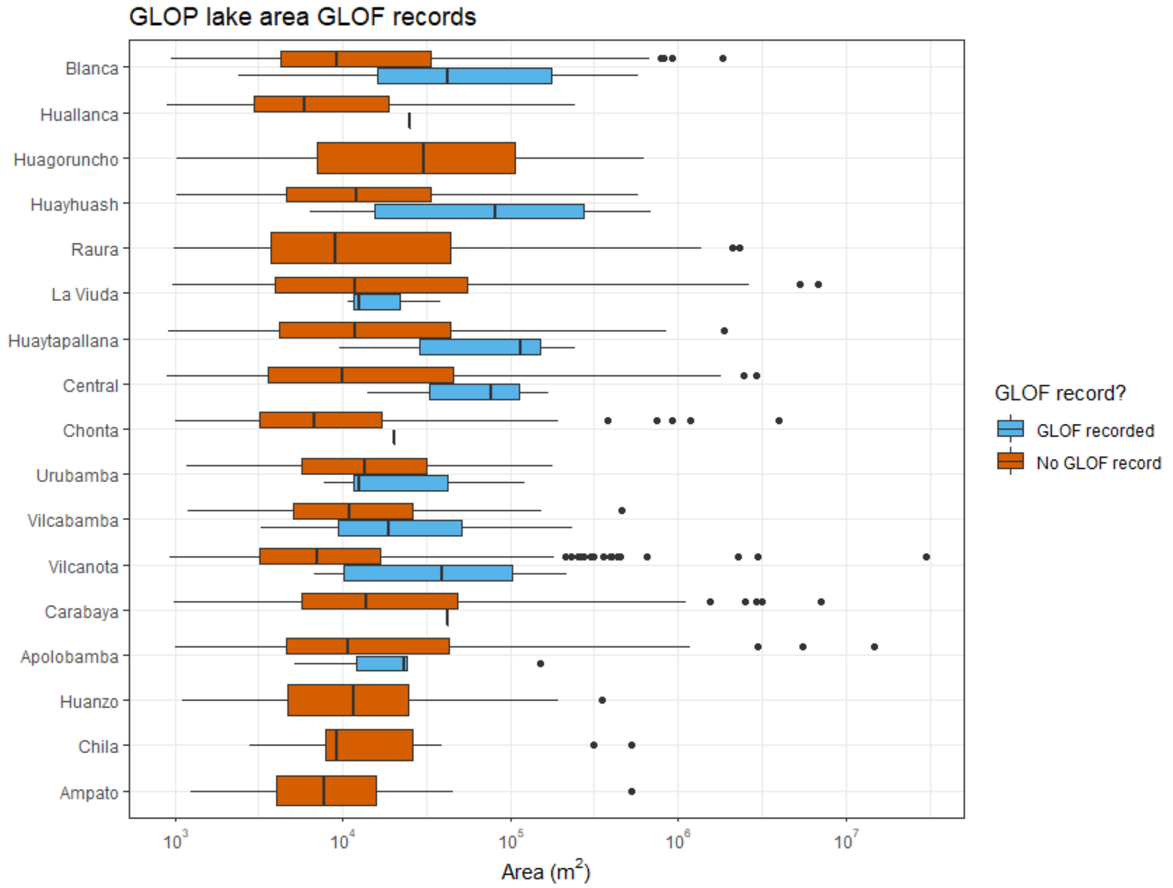
D. Results: Lake area change

- For the 2019 lake inventory (Wood *et al.*, in review) we assessed lakes which have experienced a past GLOF compared with those lakes which have no recoded GLOFs
  - In all cordilleras (with the exception or Urubamba) **lakes which have had a past GLOF** are larger **than those which have not**

	Min	1st Qu.	Median	Mean	3rd Qu.	Max
GLOF record	2394	12404	38259	104032	143986	689404
No GLOF	900	4232	10308	69052	36102	29865617

Areas shown in m^2

- The number of lakes across Peru which occur within a similar area range (between the first and third quartiles) as lakes which have experienced a past GLOF is **1845**



(Above) Showing the lake area distribution across all of the Peruvian Cordilleras. **Blue boxes** indicate lakes which **have experienced past GLOFs**, whilst **orange boxes** show the distribution of lake area in **lakes which have no recorded past GLOFs**. Generally, lake area for lakes which have had past GLOFs are larger than those which have not. This is also shown in the table (left) which provides recorded lake areas across all cordilleras by **GLOF**/**no GLOF** recorded.

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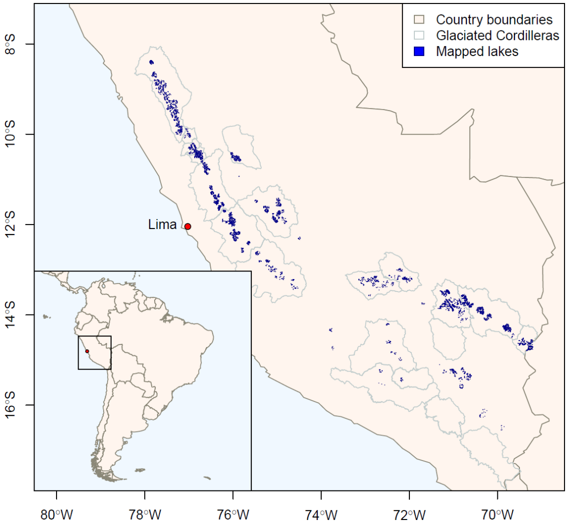
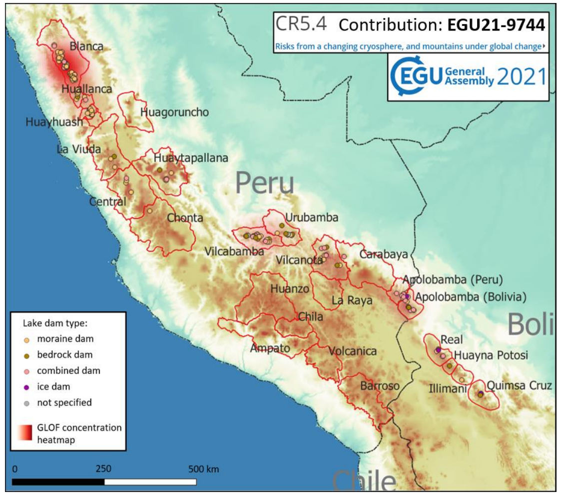
E. Summary

- We present a **new** contemporary **glacier lake inventory** and a new **GLOF inventory** for the whole of Peru
- There are several important metrics which are needed for **country-wide GLOF hazard assessments**
- Some metrics are easily available through **satellite imagery**
- Understanding **important metrics** in relation to **lakes which have failed** in the past can help to inform **country-wide** hazard assessments to help focus on **lakes which may by vulnerable in the future**





CR5.4 Contribution: EGU21-9744
Risks from a changing cryosphere, and mountains under global change
EGU General Assembly 2021

Country-wide GLOF HAZARD ASSESSEMENT

Lake Area	Glacier characteristics	Moraine characteristics	Topographic and geomorphic setting
• Lake volume estimates? • Effective volume? • Lake area change?	• Proximity to lake • Retreat rate • Calving/non calving • Glacier slope	• Type? • Width • Height • Steepness • Freeboard height • Ice core	• Landslides • Hanging ice • Connectivity to lakes • Catchment steepness

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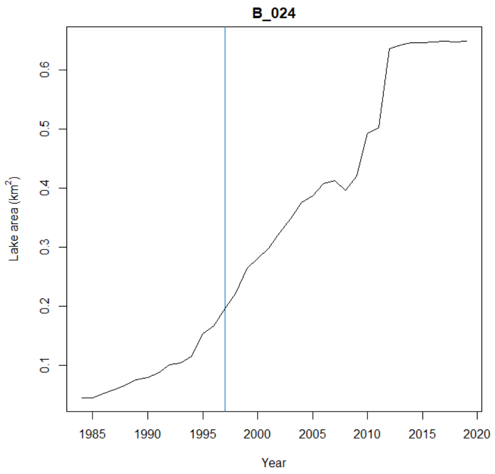
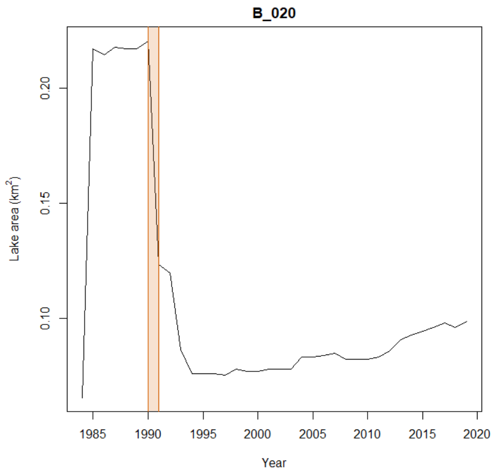
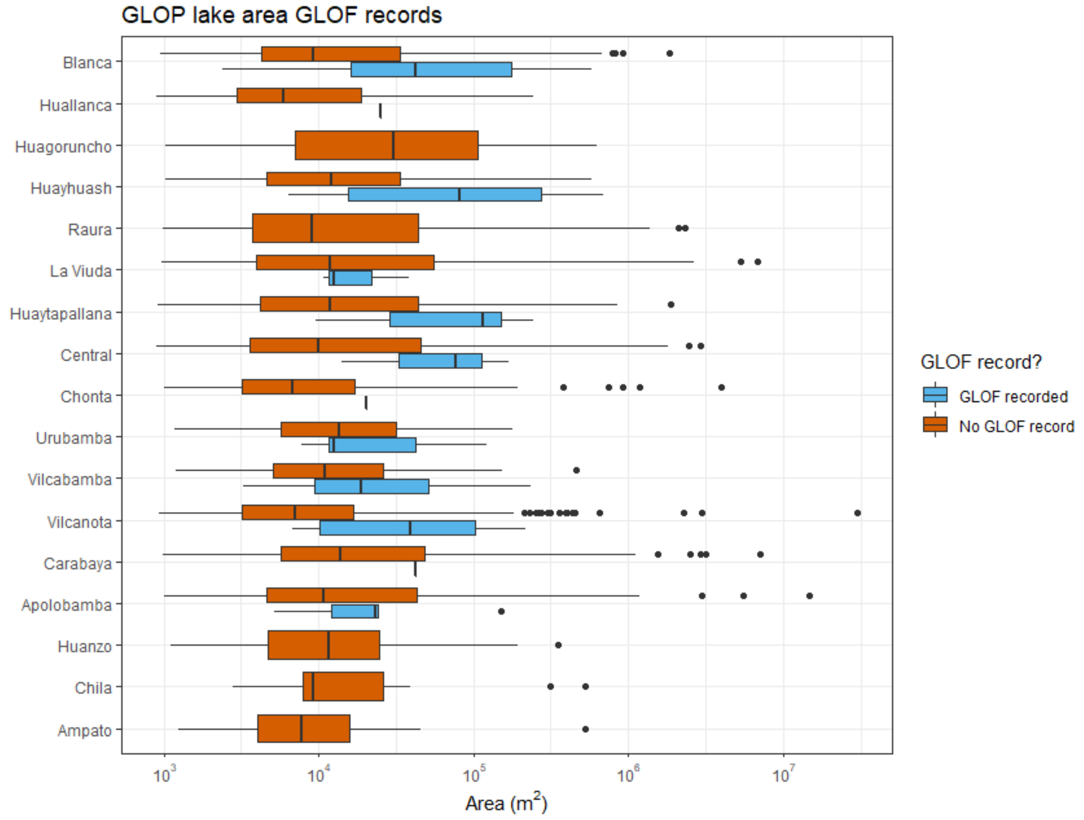
E. Summary

- We provide a first pass assessment of **lake area** across Peru and its relationship with past **GLOFs**
- **Lake area change** (particularly when derived through automatic classification) is not a reliable indicator of **GLOF risk**
- The relationship between **lake area change** and **GLOF hazards** are complex and should not be taken as proxy for risk







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Areas shown in m²

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E. Summary

- Satellite-based assessments do **not replace the value** of **detailed hazard assessments**
  - **Metrics** derived from **satellite imagery** provides a quick way of **narrowing down** the number vulnerable lakes in **country-wide** hazard assessments in order that **full and detailed hazard assessments** can be carried out to mitigate and assess risk
- **Other metrics** which are not easily detected from satellite imagery are also important for determining GLOF hazards, including:
  - Connectivity to glaciers and valley sides
  - Connectivity of slopes to lakes
  - Slope angle, height, geology
  - Protection of lakes from surrounding geomorphology by lateral moraines