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INTRODUCTION

Outbursts of glacier lakes, so-called Glacier Lake Outburst Floods (GLOFs) are considered as the most far-reaching glacial hazard (e.g., (Kääb et al. 2005)). In relatively densely populated mountain ranges such as the European Alps, the Himalayas, or the tropical Andes, where infrastructure and settlements are located within the reach of potential GLOFs, a risk is emanating from glacier lakes. Mitigation of such risks can be achieved by either structural measures, such as construction works that lower the hazard potential (e.g. Portocarrero, 2014), or non-structural measures that lower the damage potential or vulnerability by, for instance, timely alarming and evacuating the potentially affected population (e.g., Haemmig et al., 2014).

Here we present the design and implementation of an Early Warning System (EWS) for outbursts of a glacier lake in the Cordillera Blanca, Peru; including an overview of the recent history of the lake, modeling of past and potential future GLOFs, and a comprehensive description of the various components and aspects of such an EWS for GLOF hazards.

STUDY SITE

The glacial lake "Laguna 513" (4428 m a.s.l., 9°12'45''S, 77°33'00''W) is located in the Cordillera Blanca, in the tropical Andes of Peru (Fig. 1a). This mountain range has a glacier coverage of more than 500 km^2 (Racoviteanu et al., 2008), which accounts for about 25% of the World's tropical glaciers. Also more than 800 glacier lakes exist (ANA, 2014), with a majority of them draining to the río Santa Valley in the west, which is densely populated with more than 260,000 inhabitants (Mark et al., 2010, INEI 2007). Due to the vicinity of the settlements to the glacierized peaks and the numerous glacier lakes, combined with the seismic activity, the region has a long history of glacier-related disasters (Carey, 2005).

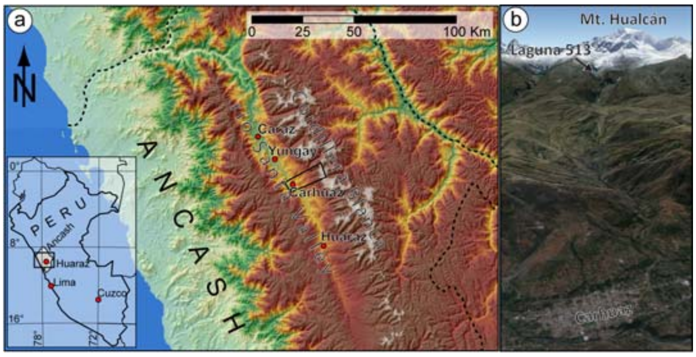

Figure 1: (a) Location of the Cordillera Blanca, Peru (Modified from Schneider et al., 2014). Black rectangle indicates the location of b. (b) Oblique view of Mt. Hualcán, Laguna 513, and the city of Carhuaz in the foreground (from GoogleEarth).

Laguna 513 (9°12’45’’S, 77°33’00’’W) is situated at 4428 m a.s.l., at the foot of Mt. Hualcán (6104 m a.s.l.). Lake formation started in the early 1970s, by filling a basin that was uncovered by the shrinking Glacier 513. In the late 1980s, when the ice retreated completely from this depression, lake formation was complete, and several smaller GLOFs were triggered by ice fall from hanging glaciers (Portocarrero, 2014). Despite syphoning initiated in the late 1980s, an ice avalanche caused another GLOF in 1991. For a further and more sustainable mitigation of the GLOF hazard, a tunnel system with a 155 m long basis tunnel and three parallel horizontal drives in the bedrock dam was constructed, which resulted in a lowering of the lake level by another 20 m in May 1994 (Reynolds et al., 1998).

April 2010 Outburst

On 11 April 2010, at about 8 a.m. local time, a rock-ice avalanche consisting of both bedrock material and glacier ice, detached at about 5400 m a.s.l. from the SW slope of Mt. Hualcán (Carey et al., 2012). The avalanche travelled over the steep glacier and finally impacted Laguna 513, causing a tsunami-like push-wave. This wave propagated through the lake and caused a spillover at the dam, despite the 20 m freeboard (Fig. 2). Traces of the wave indicate an overtopping of the dam by about 5 m, corresponding to a wave height of about 24–25 m, and causing a very high peak discharge (Schneider et al., 2014).

Figure 2: Left: Detachment zone and trajectory of the rock-ice avalanche from Mt. Hualcán. Right: Rock dam with overlaying morainic material and the breach that was formed by the overtopping wave. Circles indicate entrances of drainage tunnels. Avalanche ice is still floating on the lake. Figure taken from Carey et al. (2012).

After leaving the lake, the resulting high-velocity flood wave entrained a lot of sediment, which was then deposited again on the fan above the plane of Pampa Shonquil. The flood then crossed this plane as a hyperconcentrated flow (sediment concentration of 20–60% by volume) with relatively slow velocity, before it accelerated again in the steeper terrain below Pampa Shonquil, where again sediment was entrained, resulting in another granular debris flow. It finally affected and damaged several bridges and eventually reached the debris fan of Carhuaz, where coarse material was deposited (Schneider et al., 2014). 0.689 km^2 of agricultural land was buried and the Santa Valley highway was affected, but no lives were lost (Carey et al., 2012).

GLOF MODELING

Schneider et al. (2014) reconstructed the 2010 outburst by simulating the process cascade with an iterative approach of coupled, physically-based models. This model chain was then used to simulate potential future scenarios of different magnitudes, which finally resulted in a hazard map for GLOF hazards for the entire catchment.

Retrospective modeling of the 2010 outburst

For the model calculations, the entire process chain was divided into three main parts: the rock-ice avalanche, the displacement wave in the lake, and the GLOF, which was further subdivided into the different flow types described above. The avalanche and the GLOF were modeled with the RAMMS (RApid Mass MovementS) model (Christen et al., 2010). A Digital Elevation Model (DEM) derived from WorldView imagery acquired in 2012 (8 m spatial resolution) was used for the RAMMS modeling. The displacement wave was modeled with the hydrodynamic IBER model (IBER, 2010), using the lake bathymetry data from Cochachin (2011).

It was iteratively found, that an initial avalanche volume of approximately 450’000 m^3 is required to produce a wave that overtops the dam by 5 m (Schneider et al., 2014). The resulting spillover hydrograph from IBER (50’000 m^3 overtopping the dam in only 10 s, with an extreme peak discharge of 9000 m^3 s^{-1}) was then used again as input for the GLOF modeling with RAMMS. Friction parameters for the GLOF subsections were taken from literature (cf. Schneider et al., 2014 and references therein).

Hazard mapping based on potential future scenarios

Inundated areas modeled by RAMMS correspond well with field evidences and post-event imagery (Schneider et al., 2014). This gives confidence to the model chain, despite the considerable uncertainties of various sources. In order to produce a hazard map for the entire catchment, the widely used guidelines from Raetzo et al. (2002) were applied, which rely on three different scenarios of different magnitudes (small, medium, large). Defining such scenarios is subject to uncertainties because the underlying database for frequency–magnitude relations typically is very poor. Here, the dimensions of the 2010 event, which were similar to the 1991 GLOF, were taken for the small scenario; the medium and large scenarios involved avalanche volumes of 1 and 3 million m^3, respectively (Schneider et al., 2014). The model chain described above was again applied for the simulation of these scenarios, resulting in the values given in Table 1.

Table 1. Avalanche, spillover, and GLOF volume, as well as travel time from Laguna 513 to the apex of the debris fan of Carhuaz, as modeled for the three scenarios (small, medium, large). Modified after Schneider et al. (2014).

	Avalanche volume	**Spillover volume**	**GLOF volume**	**Travel time lake – fan apex**
Small	450’000 m^3	50’000 m^3	100’000 m^3	102 min
Medium	1’000’000 m^3	350’000 m^3	700’000 m^3	65 min
Large	3’000’000 m^3	2’400’000 m^3	4’800’000 m^3	35 min

Comparisons of the impacting avalanche volume and the spillover volume reveal that the lowering of the lake level has a decreasing effect with increasing avalanche dimensions: Whereas for the small scenario only 11% of the avalanche volume leave the lake, these volumes are almost identical (80%) for the large scenario.

According to the guidelines from Raetzo et al. (2002), flow velocities and flow heights can be translated into different levels of intensity (Fig. 3). Figure 4a shows the modeled hazard, according to the application of the schemes of Fig. 3 to the flow heights and flow velocities modeled for the three scenarios. The combination of these hazard levels into one map (by taking for each pixel the highest hazard value from the three scenarios) provides the basis for the final hazard map. This basis is then evaluated, verified and adapted in the field. The final hazard map is then produced by a generalization and taking into account the results of the fieldwork (Fig. 4b). For the final version two hazard levels (“very high” and “residual”) were added.

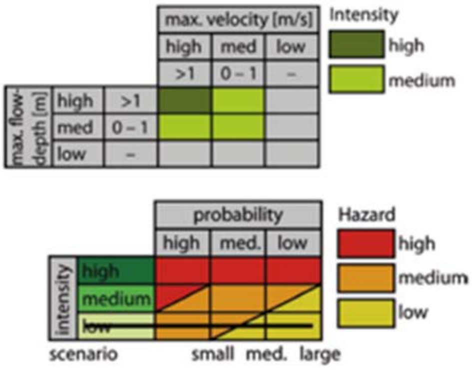

Figure 3: Top: matrix for translating debris-flow velocity and flow height to intensities (note that low intensity does not exist for debris flows). Bottom: matrix for translating the intensities of the different scenarios to hazard levels (low intensity is left away, as it does not exist for debris flows).

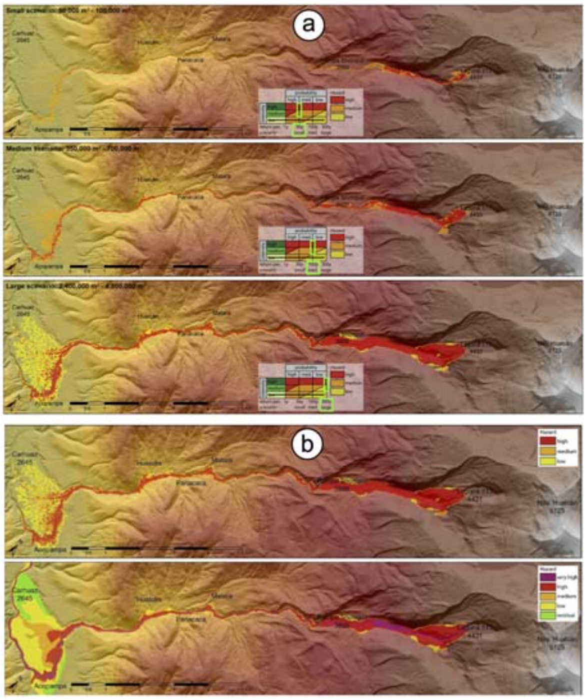

Figure 4: (a) GLOF hazards for the three scenarios. Hillshade view of the WorldView DEM in the background. (b) upper panel: combined hazard levels from the three scenarios; lower panel: generalized form, corresponding to the final hazard map for GLOFs for the entire catchment. (Figs. D. Schneider).

EARLY WARNING SYSTEM

Based on the gained insights and the improved process understanding from the reconstruction of the 2010 outburst and the modeling of the potential future scenarios, an EWS for GLOFs has been designed and implemented in the catchment.

Stations and sensors

The EWS comprises two stations, one located at the dam of Laguna 513, one in the Pampa Shonquil, a data center located in the building of the Carhuaz municipality, and a repeater station for transferring the signal from the lake to the data center (Fig. 5).

Figure 5: The four stations of the EWS. Dashed arrows indicate the direction of the signal transfer; the dashed line corresponds to the catchment margins. Background: topographic map from the Austrian Alpenverein and the GLOF hazard map.

The stations are equipped with the following instruments:

1. *Data center* (2640 m a.s.l.): Receiving antenna, screen with real-time data access, server for data storage, infrastructure for launching alarms (not implemented yet)
2. *Repeater station* (3189 m a.s.l.): Receiving and sending antenna
3. *Station Laguna 513* (4491 m a.s.l.): 2 cameras taking photos every 5 seconds during daylight times, one looking at the face of Mt. Hualcán, one observing the dam (cf. Fig. 7). 4 geophones located close to the station, continuously measuring and sending data in 5 second intervals. Receiving and sending antenna and data logger.
4. *Station Pampa Shonquil* (3600 m a.s.l.): Pressure sensor located in the riverbed, Meteorological station with sensors for measuring air temperature and humidity, precipitation, wind speed, and solar radiation. Sending antenna and data logger.

All stations are equipped with solar panels and batteries for energy generation and storage, have a mast where most of the instruments are fixed, a concreted and lockable box for the electronic equipment, and a protection fence (cf. Fig. 6). Energy availability is a limiting factor, in particular at the Station at the glacier lake, because the peaks of the Cordillera Blanca experience a much higher frequency in cloud coverage that regions further away from the main peaks. Additionally, for preventing data losses and interrupted access in case of blackouts, emergency power aggregates are available in the building of the municipality.

The geophones (devices recording ground movements and converting them into voltage) are the principle instruments to register a potential GLOF trigger. The cameras are used as a backup and possibility for overlooking the current situation; and, particularly during the test phase of the system, for relating geophone measurements to the magnitude of (avalanche) events. The pressure sensor in the riverbed at the Pampa Shonquil station adds redundancy to the system on the one hand; and, if calibrations measurements are taken, can be used for constantly recording the runoff. Next to the station at Pampa Shonquil a permanently manned hut of the wardens of the freshwater intake of Carhuaz is located. This warden would warn the authorities in case of an event (as it was the case in the 2010 event), which as well is a complementary redundancy to the system.

Figure 6: From left to right: Station Laguna 513 (inset showing the two cameras), Station Pampa Shonquil, Repeater Station, and main screen in the data center at the municipality of Carhuaz. Photos by CARE Peru.

Data center and website

All recorded data is stored first in the data logger at the respective station, then after data transmission (5 seconds intervals), on a server located in the data center and backed up on a server cloud. All data is directly transferred to a website to allow for a real-time remote access. In the data center itself – a separate office in the municipality of Carhuaz – a screen is constantly showing the data from this webpage (24/7).

The webpage is structured into different sub-pages: *Station Pampa Shonquil* with the plots of the measurements of precipitation, humidity, radiation, temperature, pressure sensor, and wind speed and an indication of the charge level of the battery; *station Laguna* with the measurements of the geophones and small images taken by the two cameras and an indication of the charge level of the battery; *cameras* showing the recent photos in higher resolution; *last event* where the geophone data (Fig. 7) and several photos are shown from the moment when the geophone data exceeded the defined thresholds; *SMS alert* with the possibility to manually send out text messages to the registered cell phones; *data download* with the possibility to download all archived dated for a selectable time range. Furthermore there is a *home*, *login*, and *about* panel.

Warning procedure

An action plan has been developed, indicating all actions to take. Related bases for decisions are indicated for different warning levels in a flow-chart type diagram (Fig. 8). For establishing such an action plan, local, regional and national laws, rules and guidelines must be considered. It is crucial that the EWS can be adopted by the prevailing hazard and emergency structures. Involved authorities include the members of the local emergency operation center (COEL), civil defense, selected government members, and the mayor, who has the power to launch the alarm initiating evacuation. This action plan is accompanied by a list of responsible persons and their phone numbers.

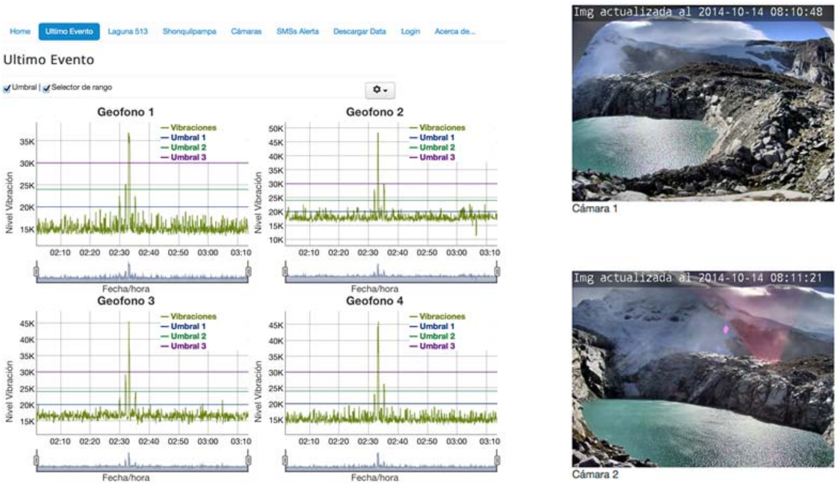

Figure 7: Left: Screenshot from the last event *subpage of the website, showing the geophone data registered during an avalanche (which did not cause an impact wave). Horizontal lines indicate the three thresholds. Right: Screenshot from the photos on the dam (top) and Mt. Hualcán (bottom)*

If the measurements of one geophone overpass a defined threshold, an SMS is sent automatically sent out to all involved persons, telling to immediately check the EWS data and information. Subsequent steps have then to be taken based on this action plan and on the available data. No alarm is launched automatically by this EWS.

The alarm module is not implemented yet, but the municipality of Carhuaz is working on this. It is planed to install one or two long-range sirens to cover the entire area of the city of Carhuaz. In parallel to the acoustic alarm, the system has the possibility to send out predefined text messages to district leaders. The populated places further up in the catchment (indicated in the map in the background of Fig. 5) are not included in the acoustic alarm concept at the current stage. However, zones with cellular signal coverage could be included in the described SMS service.

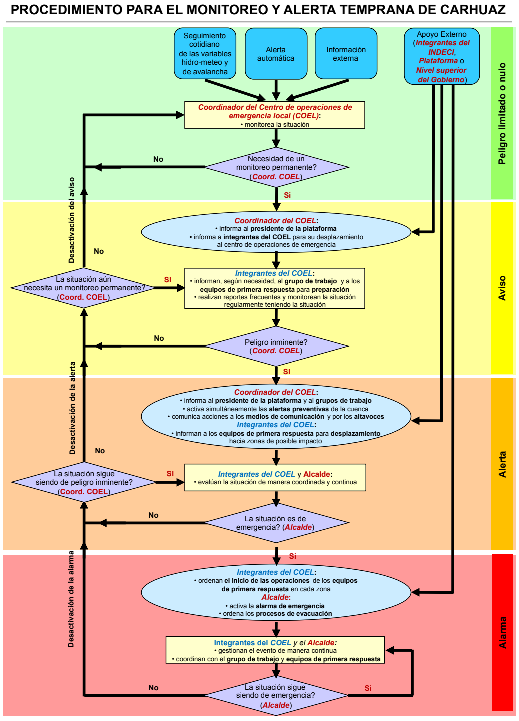

Figure 8: Flowchart-type action plan for the different alert levels.

COMMUNICATION, PREPAREDNESS AND RESPONSE

A good response of the concerned population is key for a successful EWS and requires continuous communication with the population. This includes the explanation of the concept and functionality of the EWS, as well as its potentials and limitations, and clear instructions on actions that have to be taken in case of an alarm. In this case these instructions involve the directive to immediately escape the endangered zones, and a clear indication of the evacuation route and safety zones (Fig. 9). A detailed map with all evacuation routes was developed by the civil defense of Carhuaz on the basis of the hazard map described above. Knowledge of the cultural background and the perception of both the natural environment with its related hazards and the EWS itself, are of fundamental importance for a successful communication and a positive response, in particular in rural mountain regions.

Figure 9: Information of the population of Carhuaz on the new plan for evacuation routes (left) and detailed local instructions (right). Photos from CARE Peru.

Test alarms and simulations are very effective means to train both authorities involved in the EWS and the potentially affected population. Due to the permanent seismic hazard in Peru, several emergency simulations are scheduled every year for the entire country. Such simulations, some of them taking place at nighttime, can be used to not only expose the population to a test evacuation und near-realistic conditions, but also to test the action plan and the decision process of the responsible authorities.

Data analysis and operational service

The system is currently in a test phase and not yet operational. One of the main objectives of this test phase is the establishment of the thresholds for the geophone measurements described above. Three different thresholds are applied (cf. Fig. 7) to make sure that smaller events get registered as well (lowermost threshold) and to have a direct indication of the size of the event, depending on only one, two, or even all three thresholds are overshot.

During the test phase, minor modifications and improvements at the stations are carried out. But also once the system will be operational, it will require constant maintenance due to the limited lifetime of its components and the harsh environmental conditions. On a long-term perspective, regular revisions of the design and setup, as well as re-assessments of the hazard situation in general, will be required due to the rapid changes of the involved processes.

CONCLUSIONS AND OUTLOOK

Outbursts of glacier lakes are often parts of chains of interacting processes. Schneider et al. (2014), for one of the first times, could reconstruct an outburst of Laguna 513 in the Cordillera Blanca in Peru, by modeling all involved processes. Coupled physically-based models were applied to model the triggering rock-ice avalanche, the subsequent impact wave in the glacier lake, and the resulting GLOF with its varying flow types with an iterative approach. This model chain could then be used to simulate potential future events of different magnitudes that in turn were used for developing a hazard map for GLOF hazards of the entire catchment, which also served as a basis for designing the EWS and related planning of evacuation routes.

The modular design of the EWS allows customized extensions if they become desired at a later moment. For instance, further sensors could be installed at the two stations, or further stations could be integrated into the network. As mentioned above, the small communities further up in the catchment are not included in the alarm deployment yet. The repeater station, so far only use to transmit the signal from the station at the lake to the data center, could be used to install further alarm modules in these centers by sending a signal back up to the repeater station, which would then be transmitted to new sirens located in the catchment.

First measures to reduce the hazard potential of Laguna 513 have already been realized in the early 1990s, when the lake level was lowered. These measures clearly prevented a larger catastrophe in 2010: without the additional freeboard of 20 m, the spillover would have been an order of magnitude higher or even more, with unforeseeable consequences. The presented EWS is a non-structural measure, complementing this construction, and lowering the risk by reducing the damage potential through evacuation of the population in case of an outburst. Further measures are planed to be realized at this lake, focusing on other aspects: (i) a further, 30 m lower tunnel through the bedrock dam, with the possibility to control the discharge, and (ii) a monitoring of slope stability in the surrounding of the lake with spaceborne radar interferometry (InSAR) in the framework of a project from the European Space Agency (ESA). (i) will lower the lake level and thus the hazard potential further; in parallel, the outlet control will allow to retain water in the lake after the wet season and compensate water scarcity during the dry period caused by shrinking glacier coverage. (ii) will help to detect terrain deformations from space with data from ESAs Slope Stability and Glacial Lake Monitoring (S:GLA:MO) project. In the case of Laguna 513, this could help to anticipate mass movements that potentially could trigger impact waves. In contrast to the real-time observation of the EWS, this monitoring will provide the possibility for forecasting potential adverse developments on a short to mid-term time range. This combination of structural and non-structural hazard reduction measures, real-time monitoring, and forecasting, supplemented by the multi-purpose installation in the planned further tunnel, would make Laguna 513 a pioneer case for hazard reduction and prevention approaches and integrative high-mountain risk management.

Acknowledgements
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