GLACIAL FLOODING AND DISASTER RISK MANAGEMENT KNOWLEDGE EXCHANGE AND FIELD TRAINING

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Glacial lakes and emerging risks in the Cordillera Blanca
Wilfred Haeberli, Marcelo Somos-Valenzuela and Cesar Portocarrero

1. Introduction

Continued atmospheric warming induces striking changes of most glaciers around the world (WGMS 2008). The formation of new lakes in de-glaciating high-mountain regions (Linsbauer *et al.*, 2012) strongly influences landscape characteristics and represents a significant hazard related to climate change (Haeberli *et al.* , 2010; Kattelmann 2003; Richardson and Reynolds 2000).

An increasing number of numerical modeling studies indicate that mountain glaciers are likely to continue vanishing (Zemp *et al.* 2006); that a fifth of Canada's Arctic Archipelago glaciers may disappear by the end of the century (Lenearts *et al.* 2013); that up to 50 percent of the Andes glaciers may have already been lost to climate-induced melting (Rabatel *et al.* 2013); and that Himalayan glaciers are reported to be losing mass as well, although with notable exceptions in the Karakoram and Northwestern Himalaya (Bolch *et al.* 2012). Major effects of this trend in glacier recession are increased variability in water supplies in some regions (Huss, 2011) and flooding risks from lakes formed at receding glaciers (Clague and Evans, 2000; Haeberli *et al.*, 2010).

The goals of this module and visit to Laguna Llaca are to

- (a) Understand the formation, characteristics and further evolution of new lakes due to glacier retreat in the Cordillera Blanca;
- (b) exchange knowledge end experience regarding the assessment of potential hazards due to glacier floods and debris flows;
- (c) discuss corresponding possibilities of hazard prevention and safety systems; and
- (d) consider consequences of glacier retreat to fresh-water supply and related adaptation strategies.

2. Cordillera Blanca

Glaciers in the Andes of Peru provide fresh water to the arid western part of Peru during the dry season when little to no rainfall occurs (Vuille *et al.*, 2008). The west coast of Peru uses the water coming from the high mountains for agricultural, domestic and industrial purposes. In Peru, the main source of electricity generation is hydropower, representing 80% of the electricity in the country (Vergara *et al.*, 2009). Georges (2004) estimated that the glacier-covered area in the Cordillera Blanca of Peru had decreased from 800-850 km^2 in 1930 to 600 km^2 at the end to the 20th century. On the other hand Silverio & Jaquet (2005) estimated that Cordillera Blanca glaciers reduced from 643 ± 63 km^2 to 600 ± 61 km^2 between 1987 and 1996, and in another estimation the total area was reduced by 26% from 723 to 535 km^2 between 1970 and 2003 (Tacsi *et al.*, 2008). Tacsi et al. (2008) estimated that the reduction from 1970 to 1996 was 15.46% (0.6% per year) and from 1996 to 2003 was 10% (1.4% per year). Racoviteanu et al., (2008) found 571 glaciers covering an area of 569 km^2 and experiencing a decrease in glacier area of -0.68% per year over the thirty-three year period 1970 – 2003, representing a 22.4% decrease in area over that period. Current losses can, therefore, be estimated at about 1% per year.

As a consequence of glacier vanishing, many new lakes formed in the Cordillera Blanca, fundamentally changing hazard potentials for the population. Examples in Peru of corresponding historical to recent incidents and catastrophes are listed in Table 1. The 2010 ice/rock avalanche from the summit part of Nevado Hualcán into Lake 513 generated push waves that overtopped the bedrock threshold of the lake and produced a chain of flood waves and debris flows reaching the town of Carhuaz. Preventive lake-level lowering by artificial tunnels in the 1990s already had created a free-board of 20 meters and certainly helped avoiding a major catastrophe with many people killed (Carey *et al.*, 2011). Another example of evolving hazards related to new lakes is Lake Palcacocha. This lake was declared in an emergency state since its level is considered higher than the safe level (Diario la Republica, 2010). The moraine dam is assumed to be able to fail, to abruptly release a huge volume of water from the lake and to create a flood wave and/or debris flow (Instituto Nacional de Defensa Civil, 2011).

Long-term slope destabilization due to warming and degrading permafrost in Peru concerns steep summits above about 5000 m a.s.l.. Related low-probability but high-magnitude ice/rock avalanches are especially dangerous in connection with lakes forming at the foot of steep mountain walls (for instance Artesonraju and the new lake probably forming soon at the flat tongue of Glacier Artesonraju), because they can trigger large impact waves permafrost (Carey *et al.*, 2011; Haeberli, 2013). Not only the ice/rock avalanche of 2010 into Laguna 513 but also the famous and devastating Huascarán rock/ice avalanche of 1970 had there starting area in warm/degrading permafrost rocks. Concerning such slope instabilities it is important to understand the concepts of long-term disposition, short-term disposition and trigger effects. Primary long-term disposition refers to the factors geology (lithology, layering, fracturing), topography (vertical extent, slope) and ice conditions (ice cover, hanging glaciers, permafrost) - i.e. always to a *combination of factors*. Short-term disposition refers to changes in these factors: With ongoing climate change, ice conditions are critical because among the primary long-term disposition factors they are changing by far most rapidly and fundamentally. Trigger effects leading to discrete events mainly include earthquakes, extreme snow melt, heat waves, heavy precipitation (Haeberli, 2013; Huggel *et al.*, 2010).

Evaluation of hazard posed by glacial lakes must be based on systematic information about lake types, dam characteristics, outburst mechanisms, down-valley processes and possible cascades of processes. In addition changes in climate patterns are likely to increase the frequency of rock/ice avalanches as a consequence of the reducing in the stability of permafrost bedrock and steep glaciers in cold mountain regions such CB ((Fischer *et al.*, 2012, 2013): A detailed study carried out on the large Monte Rosa east face in the European Alps (Fischer *et al.* (2013) documents that rates of rock and ice losses in such mountain flanks are not only increasing but can also have self-reinforcing effects.

Table 1: Main catastrophic events in Ancash.

Year	Event	Year	Event
1702	Inundación de la ciudad de Huaraz	1953-1959	Aluvión en la Laguna Tullparaju – Huaraz
1725	Aluvión que desapareció el pueblo de Ancash	1962	Aluvión en Ranrahirca del Nevado Huascarán
1725	Avalanchas y aluviones en Huaraz	1965	Aluvión en la Laguna Tumarina – Carhuascancha
1869	Aluvión en Monterrey - Huaraz	1970	Aluvión en Yungay y Ranrahirca
1883	Aluvión en Macashca cerca a Huaraz	2001	Avalancha sobre la laguna Mullaca, produciendo su desborde
1917	Aluvión del Nevado Huascarán sobre Ranrahirca	2002	Derrumbe sobre la laguna Safuna Alta, produciendo oleajes de 77m de altura
1938	Aluvión en la quebrada Ulta - Carhuaz	2003	Derrumbe sobre la laguna Palcacocha, produciendo su desborde y desabastecimiento de agua potable en la ciudad de Huaraz por 6 días.
1941	Aluvión en la cuenca del Río Pativilca	2003	Avalancha del Nevado Huandoy, produciendo 09 víctimas
1941	Aluvión en Huaraz	2006	Desborde de la laguna Matara (Huari), produciendo daños en infraestructura
1945	Aluvión sobre las ruinas de Chavín de Huantar	2008	Desborde de una laguna en formación en la cabecera de la quebrada Cojup
1950	Aluvión en la laguna Jancarurish destruyendo hidroeléctrica	2009	Deslizamiento en Rampac Grande (Carhuaz), 09 muertos
1951	Dos aluviones en la laguna Artesoncocha - Laguna Parón	2010	Avalancha de roca y hielo sobre la laguna 513, produciendo su desborde; daños a la infraestructura.
1952	Aluvión en la Laguna Millhuacocha – Quebrada Ishinca	2012	Rompimiento de dique morrenico en Artison Baja

3. Glacier lakes: examples in the Cordillera Blanca

Lagunas Arhuaycocha y Artison

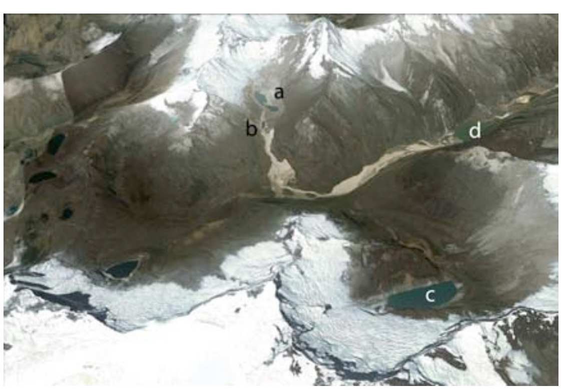


Illustration 1: Lagunas Artison alta (a), Artison baja (b), Arhuaycocha (c) y Jatuncocha (d); Google Earth 8/3/2012

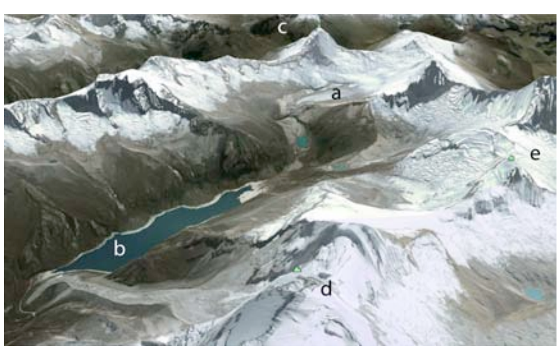
In the 1960s already, a dam of loose material 6 m high and with two outlets in its base was built at the lower end of Laguna Jatuncocha (8°55’45’’S/77°39’30’’; Illustration 1). This dam worked as a retention structure when in February 2012 the Laguna Arteson Baja higher up in the same catchment overtopped and breached its dam consisting of loose moraine material and debris-flow deposits, lowering abruptly the level of the lake and causing debris flow, the traces of which can easily be recognized in Illustration 1. As can be

seen in Illustration 2, the level of Laguna Artison Baja had been considerable higher before the event. The artificial dam structure at Laguna Jatuncocha certainly helped to considerably reduce the effects of the sudden drainage of Artison Baja.
Within the same complex of lakes in the catchment above Laguna Jatuncocha, there is also Laguna Artison Alta, with a volume of 1.4 million cubic meter of water. This lake has a solid rock dike. However, it is exposed to potential avalanches of ice, which can create huge impact waves, overtopping the rock dam and initiating a cascade of effects downstream, affecting Artison Baja and Jatuncocha.

Illustration 2: Traces of slope instabilities and of earlier lake level at Laguna Artison Baja (Foto CP, May 2013). The slope instabilities may possibly have triggered the outburst.

In adittion there is Laguna Arhuaycocha with a volumen of 19 million cubic meter of water in another part of the catchment. This lake is also exposed to ice avalanches, which can release a large amounts of water downstream, affecting Laguna Jatuncocha.
Although the structure built 50 years ago in Laguna Jatuncocha reduced the risk during the Laguna Artison Baja GLOF, it may not sufficient to prevent future and more extreme events. Therefore more detailed investigation and additional constructions are needed in order to increase the protection of downstream communities. Such projects could possibly be combined with tourist development and/or hydropower production.
At the upper end of Laguna Jatuncocha is a flat, around 4.5 km long valley section, which works as an energy disperser and could store millions of cubic meters of water. During full flood retention, however, the two 1.8 m diameter pipes in the dam allow for a maximum possible discharge of about10 m^3/s. Such a flow can produce intense erosion in the steep riverbed downstream, potentially producing a debris flow, which could destroy important infrastructure along the riverbed. It has therefore been recommended to put water level sensors and two gates with remote control to regulate the flow during extraordinary events. In view of such extraordinary events, the height and stability of the dam should also be reconsidered. An early warning system would be appropriate.

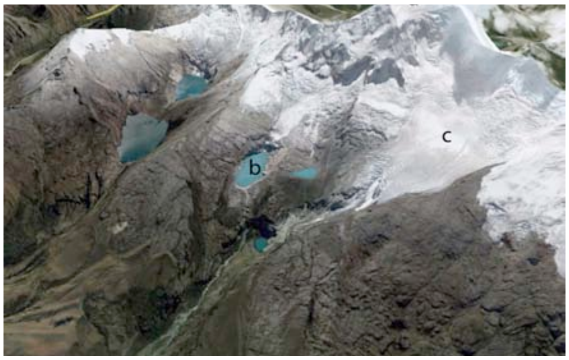
Lagunas Artesonraju/Parón



Ilustration 3: Glaciar Artesonraju (a) y Laguna Parón (b); Nevados Artesonraju (c) and Huandoy (d); Google Earth 8/3/2012

Laguna Parón has been regulated for combined flood protection, hydropower production and regular water supply since 1970 by a high-technology tunnel that controls the level of the lake. However, new lakes are forming in the catchment above Laguna Parón (Illustration 3). The retreat of the flat tongue of Glacier Artesonraju will soon enable the formation of a lake, which could end up with a volume of millions of cubic meters of water. This new lake is exposed to potential rock/ice avalanches of considerable volume, which can produce impact waves overtopping the reservoir and affecting Laguna Parón. Corresponding flood waves can be kept under control as long as an adequate free-board is guaranteed for Laguna Parón. Laguna Parón is indeed an early and successful pioneer example of a multipurpose structure related to lake management in high mountains subject to effects from climate change.

Laguna 513/ Pampa de Shonquil



Ilustration 4: Nevado Hualcán (a), Laguna 513 (b) y Pampa de Shonquil (c); Google Earth 7/16/2003.

Ilustración 6: Small GLOF after the avalanche in Lake 513. (Photo credit: D. Luis Mesa)

Lake 513 started forming in the 1980s in the Nevado Hualcán mountains (9°12'45''S/77°33'00''W) near Carhuaz, Ancash (Illustration 5). The massive bedrock dam is mainly granodiorite. Three artificial tunnels were installed already in the 1980s to lower the lake level and create a free-board of 20 m as a protection against impact waves from expected ice avalanches. This system was tested by an ice/rock avalanche event on April 11, 2010. The wave generated by the avalanche overtopped the lake threshold by about 5 m. Due to the safety system, the resulting flood event can be judged to have been "minor" in comparison with what would most likely have happened without the artificial tunnels. The event nevertheless affected the population and infrastructure, among others, by destroying the fresh-water intake (Illustration 6) system and cutting the fresh-water supply for the town of Carhuaz during one week.

Even larger events cannot be excluded for the future. An early warning system was installed and is now being tested/calibrated. Extensive modeling exercises concerning the involved process chains were carried out in order to define hazard zones and escape possibilities. Installing a flood retention structure in the flat Pampa de Jonquil could be a long-term option.

Laguna Palcacocha

This lake (Illustration 7) is located at 9°23′40”S, 77°22′40”W in the Ancash Region in

Ilustration 7: Left: Laguna Palcacocha (Foto WH, January 2011). Right: Inundation in the city of Huaraz 1941 following the outburst of Laguna Palcacocha (Morales-Arnao, 2011)

the Cordillera Blanca at an elevation of 4,567 m in the Quillcay sub-basin, province of Huaraz, Peru. The Lake drains into the Quebrada Cojup, which drains to the Quillcay River. The Quilcay River passes through the City of Huaraz giving its water to the Santa River, which is the main stream of the basin. This location has a special interest since the city of Huaraz, which is located at the bottom of the Quillcay sub-basin, was devastated by a flood released from Laguna Palcacocha on December 13, 1941. In that opportunity, many lost their lives (Vilimek *et al.* 2005, Carey, 2010). According to the Report of Hazard 003-12/05/2011 from the National Institute of Civil Defense of Peru, in 1941 the Lake had an estimated pre-event volume of 10 to 12 million m^3 of water. In 1974, some structures were built in order to keep a safe (low) water level in the Lake (Figure 8). The volume in 1970 was 500,000 m^3 but with the retreating glacier tongue increased to about 17 million m^3 of water in 2011 (Table 1). Ice/rock avalanches from the steep surrounding slopes can now directly reach the lake. According to Hegglin and Huggel (2008), a process chain of debris flows and hyperconcentrated flow from Laguna Palcacocha already had a high probability of reaching the town of Huaraz with a volume of 3 million m^3 at the time of their study. Currently there are some actions toward reducing the level of the Lake using siphons. A more definitive structure could probably be put in place since the relatively flat/stepped topography (long profile) of the Quebrada Cojup offers possibilities to install retention structures at several points along the river. Such structures would could protect the city of Huaraz from potential outbursts of Laguna Palcacocha as well as from other (smaller) lakes in the same catchment. Possible combinations with irrigation and/or hydropower production would have to be investigated.

Note: Illustrations 1 to 7 were taken with authorization from GLACIARES (in review): Proyectos de ingeniería multipropósito incluyendo protección contra crecidas, producción de energía y demanda de agua en las cordilleras peruanas: principios, potencial y desafíos. Informe preparado de Wilfried Haeberli, Javier García-Hernández, Sebastián Guillén Ludeña con comentarios de Christian Huggel y Cesar Portocarrero. A ser publicado en 2013 (Haeberli *et al.* 2013 in review).

4. Field trip to Laguna Llaca

Laguna Llaca is a moraine-dammed lake located a 4409 m a.s.l. at the top of Quebrada Llaca to the northeast of Huaraz and easily accessible via an access road. A reinforced outlet structure in the terminal moraine had already been installed at an early stage but was damaged by the 1970 earthquake. Until 1978, a new reinforced outlet structure with an ARMCO tube 48'' in diameter at its base was installed to create a lake free-board of 10 m. With continued retreat of the heavily debris-covered glacier tongue, the lake continues to grow into the direction of the steep hanging glaciers and permafrost rock walls of Ranrapalca.

Assessing hazard potentials at Laguna Llaca

The primary goal in assessing high-mountain hazards is to (1) gain an overview of the involved hazardous phenomena and processes, (2) set priorities concerning steps to be taken, (3) define responsibilities, (4) clarify the acceptable risk and (5) establish relevant observational and monitoring systems to acquire the necessary quantitative information. Huggel *et al.* (2004) provide practice-oriented decision trees for hazard assessments in high mountains (especially the European Alps), which can to a large degree also be used in the Peruvian Cordilleras. These procedures should be a standard for all those dealing with hazard assessments in cold mountain regions and will be discussed in the field. Google Earth can greatly help to quantify involved parameters. The following is a brief example for Laguna Llaca.

The longest historically known run-out distance of a rock/ice avalanche in the well-documented Alps was about 6 km. As a first step, this empirical value helps judging, whether rock/ice avalanches from Ranrapalca can reach Laguna Llaca. The answer is clear: yes (the Laguna is at a distance of about 3.4 kilometers with respect to the steep Ranrapalca slopes and will even come closer with further expansion). Refinement of this first rough assessment is to apply the rule that ice avalanches, especially when traveling over ice surfaces - can reach run-out distances three times the drop height. At Ranrapalca, the drop height to Laguna Llaca would be about 5800-4500 = 1300m and the corresponding run out distance around 4 km, enough to reach the Laguna at 3.4 km, especially with its further growth towards the mountain slope. Note that this calculation is independent of volume, but that the probability of an ice avalanche reaching the lake is higher with larger volumes and even higher if a rock fall from warm permafrost is involved. With this rough assessment it is already clear that a process chain must be considered with a possible impact wave and a following flood wave or debris flow. For coarse-grained debris flows we empirically assume a reach of five times the drop height. In the case of Laguna Llaca the drop height to the Rio Santa would be 4500-3000 = 1500m and the corresponding run-out distance about 7.5 km. The valley bottom, however, is at a distance of some 11 km. This means that - similarly to the historical Palcacocha outbursts, one single debris flow would not reach the valley bottom. It could, however, deposit the sediments in flatter parts of its trajectory and the released water could produce a flood or even start eroding steeper parts of the lower river section and produce a secondary debris flow reaching Rio Santa.

This type of estimation is what can be done as a first assessment "in the field" and with the help of Google Earth. More detailed and refined assessments would need numerical modeling: what wave height could be produced in the lake by what type of events and can be retained by the existing artificial outlet structure and the correspondingly lowered lake level of Laguna Llaca, where would debris flows form and where could hyper-concentrated flow be possible, etc.. The case of Laguna Llaca also illustrates of a fundamentally important non-physical aspect: we are dealing with low-probability, high-magnitude events. The decision about what measures should be taken to protect people and infrastructure from devastating low-probability events is always a political one and must be compared with other risks in the life of people living and working there. However, the probability of a high-magnitude event is steadily increasing with the disappearance of ice, the growth of the lake towards the steep mountain flanks and the continued destabilization of ice mountain slopes.

7. Conclusions and future challenges.

- Like most glaciers in the world, glaciers in Cordillera Blanca have been strongly shrinking (currently about 1% per year area loss) after the Little Ice Age; as a consequence, numerous new lakes have been und are still forming, which are dammed in some cases by unstable moraine complexes and in most of the cases exposed to avalanches of ice and rock. The melting process has accelerated during the last decades and is predicted to continue into the future.
- The frequency of rock/ice avalanches events from the highest peaks (> 5000 m a.s.l.) is likely to increase as a consequence surface-ice vanishing and permafrost degradation.
- Many lakes formed at the foot of extremely steep icy mountain peaks in the Cordillera Blanca have a considerable potential of being overtopped due to impact waves caused by ice/rock avalanches, producing inundations downstream.
- The safety systems implemented in Cordillera Blanca have avoided major catastrophes; examples are Lake 513 and Laguna Jatuncocha.
- Successful hazard prevention work like at the Lagunas 513, Palcacocha or Jatuncocha needs constant monitoring and judging of the rapidly evolving situation (lake growth, disappearance of flat glacier tongues, slope instabilities, etc.); long-term options such as downstream flood retention should be carefully investigated and possible combinations/synergies with water supply and hydropower projects should be evaluated.

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