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TECHNICAL REPORT

THE GLACIAL LAKE HANDBOOK

REDUCING RISK FROM DANGEROUS GLACIAL LAKES IN THE CORDILLERA BLANCA, PERU

February 2014
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February 2014

Prepared for:

United States Agency for International Development

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ACRONYMS

ANA	National Water Authority (Peru)
CAPA	City Adaptation Programs of Action
CCRD	Climate Change Resilient Development
GLOF	Glacial Lake Outburst Flood
HiMAP	High Mountains Adaptation Partnership
INRENA	National Institute of Natural Resources (Peru)
IPCC	Intergovernmental Panel on Climate Change
IRG	International Resources Group
LAPA	Local Adaptation Plans of Action
LGM	Last Glacial Maximum
MASL	Meters Above Sea Level
NAPA	National Adaptation Plans of Action
USAID	United States Agency for International Development

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I. PREFACE

Mountain areas are particularly vulnerable to the impacts of climate change. Today's rapid snow and glacier melting initially increases runoff in some regions, but lack of a glacial buffer ultimately causes decreased reliability of dry season stream flow, which affects agriculture, ecosystems, hydropower, and water supply. These changes are superimposed on other drivers in local society, creating profound impacts on mountain communities and downstream populations. This is especially true in the heavily glaciated Hindu Kush–Himalayas and Andes regions. The changes pose unique challenges for adaptation to climate change response, including more variable seasonal patterns and increased threats of glacial lake outburst floods (GLOFs), which have strong impacts on economic, environmental, regional, and social systems. Considerable uncertainty surrounds future water supplies, storage, and hazards in changing climate patterns.

In recent decades, Peru has experienced what most experts are now predicting for other glaciated mountains throughout the world—shrinking glaciers with emerging lakes that sometimes release deadly GLOFs. This Peruvian experience has led to expertise in glacier hazard management that is perhaps unmatched in the world. The first local risk-reduction efforts in Peru's major mountain range, the Cordillera Blanca, began in 1942 after a GLOF destroyed much of the city of Huaraz, killing an estimated 5,000 people. Nine years later, in 1951, the national government officially established the Control Commission of Cordillera Blanca Lakes that is today known as the Glaciology and Hydrological Resources Unit. The glaciology office conducted engineering projects to reduce the risk of 34 dangerous glacial lakes. By draining and containing glacial lakes before they produce outburst floods, these engineers have likely prevented many catastrophes. It is believed that these efforts saved the cities of Huaraz in 1959, Huallanca in 1970, Carhuaz in 1991, Huaraz in 2003, and Carhuaz again in 2010. And that's only the known close calls considering that most of these lakes lie high in the mountains where events go unnoticed.

Working with limited government resources—a situation similar to that of Nepal and other developing countries—Peru's Glaciology Unit is now a leader in tropical glacier research and glacial lake engineering to prevent outburst floods. So that the world may benefit from this Peruvian expertise, the USAID-funded High Mountains Adaptation Partnership (HiMAP) feels that this knowledge should be shared with mountain dwellers worldwide. The following technical report, *The Glacial Lake Handbook*, captures the lessons learned by Ing. César A. Portocarrero Rodríguez, during the course of a 40-year career, devoted his efforts to the reduction of GLOF risks in the Cordillera Blanca. We hope that the experience and guidance provided by the *Handbook* will be of use to decision makers, engineers, local people, and scientists in other regions of the world currently experiencing the phenomenon of receding glaciers accompanied by the formation of potentially dangerous lakes.

Alton C. Byers and Daene McKinney, HiMAP Co-Managers

February 2014

2. USAID SUPPORT TO WORK ON GLACIAL LAKES IN PERU

The Climate Change Resilient Development (CCRD) project is designed to advance the understanding of climate adaptation in priority sectors, geographic areas, and sensitive landscapes. Under CCRD, the High Mountains Adaptation Partnership (HiMAP) was established with the goal of increasing awareness for the critical importance of high mountain watersheds. HiMAP was funded by the United States Agency for International Development (USAID) and implemented by Engility Corporation under co-management of The Mountain Institute and the University of Texas at Austin.

HiMAP contributes to glacial lake management in both Peru and Nepal through a combination of field activities, small grants, and workshops.

This first activity supported and implemented international workshops organized by HiMAP personnel ("Adapting to a World Without Glaciers" in 2009 in Peru; "Andean-Asian Glacial Lake Workshop and Expedition" in 2011 in Nepal; and "Glacial Flooding and Disaster Risk Management" in 2013 in Peru).

The second major area of support has been through the HiMAP Climber-Scientist Small Grants program. This program provided field-based, hands-on opportunities to scientists and practitioners working in high mountain regions. Particular focus was placed on the generation of knowledge regarding the impacts of climate change, interaction between highland and lowland communities, and methods for protecting fragile alpine ecosystems. The work in Peru included studies on integrated and participatory risk management in the Lake Parón basin (see Case Study 3.2) by grantees Adam French (French, 2013) and Laura Read (Read, 2013). It also included work on changes in the headwaters of the Cordillera Blanca as glaciers have receded because of climate change by grantee Raúl Augusto Loayza Muro (Loayza, 2013). These studies were presented at the "Glacial Flooding and Disaster Risk Management" workshop held in July 2013 in Huaraz, Peru.

The final area of support has been through the field activities of the HiMAP implementing partners, The Mountain Institute and the University of Texas at Austin. In combination with the development of Local Adaptation Plans of Action (LAPAs) with communities living near or below potentially dangerous lakes, this work has examined the technical issues related to the emerging glacial lake at the Arteson Glacier in the Lake Parón Basin (see Case Study 3.2) and the situation at Palcacocha Lake (Chisolm, 2013, and Somos and McKinney, 2011) (see Case Study 3.1). In addition, HiMAP develops technical information to reduce risk from Imja Lake in the Khumbu region of Nepal (Somos, et al., 2012 and 2013).

3. OVERVIEW OF GLACIERS, GLACIAL LAKES, AND MANAGEMENT PRACTICES

This section presents lessons learned by Peruvian engineers who worked for more than 70 years on glacial lake management methods, mostly in Peru's highest mountain range, the Cordillera Blanca.

3.1. PURPOSE OF THIS REPORT

Although glacial lake outburst floods (GLOFs) have occurred repeatedly in many places around the world, perhaps no country has as much experience with managing such lakes as Peru. This technical report is a distillation of the experiences and knowledge acquired during seven decades of active lake management. The goal is to provide lessons learned and case studies that may benefit the global community as each country addresses its own glacial lakes challenges. We stress that local efforts must adapt to the unique context of each country, lake, and valley, and that each case requires action based on the best locally available knowledge and engineering.

Peru, along with other developing countries, must rely on limited research across the wide range of disciplines that are important to glacial lake management, including geography, climatology, anthropology, animal science, and botany, as well as the social and political sciences. Mitigation strategies should involve the development sector because managing water as a resource is as important to many local populations as is disaster risk management for GLOFs. Wisely managing glacial lakes requires inter-institutional work that is most productive when done cooperatively.

3.2. HISTORY OF PERU'S GLACIOLOGY UNIT AS BACKGROUND TO THIS REPORT

The Cordillera Blanca continues to be the subject of many national and international studies since the 1930s. Many have focused on observing and evaluating the distribution and stability of the numerous glacial lakes in the range. In 1940, the Austrian geographer and cartographer Hans Kinzl warned that Lake Palcacocha was at risk of breaching its moraine dam and flooding the city of Huaraz. His advice was ignored. In 1941, Palcacocha's moraine broke and the resulting GLOF killed around 5,000 people in Huaraz.

In 1951, Peru's president Manual A. Odría established the Control Commission of Cordillera Blanca Lakes to assess conditions contributing to glacial lake stability. The central tasks were to prepare an inventory of glacial lakes, identify those that posed a risk, and adopt adequate prevention measures.

In 1969, the Peruvian government created the state electric company, Electroperú and with it the Glaciology Unit. The Glaciology Unit was added because the government and the company believed that GLOFs could severely hamper regional development. Dedicated teams of scientists and engineers were hired to research, evaluate, and develop methods to decrease the risk of potentially dangerous lakes. Over the decades, the Glaciology Unit grew to about 70 permanent staff supported by up to 300 temporary workers during construction projects. These teams were accountable to government and to society for understanding changes in glaciers and the emergence of dangerous lakes so that risks could be addressed in a timely way with basic preventative measures.

The original Glaciology Unit was disbanded in 1996 due in part to increased privatization of hydroelectric works. Some aspects of the Glaciology Unit have continued under various authorities, including Huascarán National Park, the Hidrandina electric company, Electroperú, the National Institute of Natural Resources (INRENA), and the National Water Authority (ANA).

Some case studies in this report also refer to the department of "Glaciology and Lake Security" and the "Glaciology and Water Resources Unit," which existed in Peru during different stages. (For a thorough review of Peru's history of glacial lake management, see *In the Shadow of Melting Glaciers: Climate Change and Andean Society*, by Mark Carey, Oxford University Press, 2010.)

Under one official body or another, safety measures have been implemented in almost 40 glacial lakes in the Cordillera Blanca and two in the Junín Department of central Peru. The most obvious success story is Lake 513 on Nevado Hualcán, where lowering the lake by 20 meters prevented a catastrophic peak surge discharge on 11 April 2010. This event would otherwise have caused a tremendous flood of the Chucchún River and the downstream communities of Acopampa and Carhuaz (see Case Study 5.3: Lake 513).

The principle author of this report, César A. Portocarrero Rodríguez, is a Peruvian civil engineer who started working in the Glaciology Unit in 1973 and headed the organization from 1989 to 1996. During that time he personally worked on 18 glacial lake projects, several of which are documented in this report. Since the disbanding of the original Glaciology Unit, Portocarrero has consulted on various environmental engineering projects in Nepal and Peru.

3.3. FACTORS THAT INFLUENCE RISK MANAGEMENT OF GLACIAL LAKES

Preventing glacial lake outburst floods first requires identifying the risk. This requires visiting each lake in the field by traveling long distances on foot or on horseback. During the last decade it has become possible to use satellite images for the glaciological inventories, but these have proven unreliable for dangerous lakes identification because the satellite images are usually out of date. Thus, on-site verification must be conducted on a frequent basis. Conducting only sporadic or occasional glacial monitoring reduces the likelihood of detecting critical changes as dangerous lakes develop.

The following section presents factors that need to be considered when assessing the risks of glacial lakes.

3.3.1. GLACIER CHARACTERISTICS

These include slope, the magnitude of crevassing, the magnitude of fragmentation, and estimated thickness. Thickness measurements become particularly important to the development of predictive models of outburst flood volumes under different scenarios. Recently, it has become possible to measure ice thickness and other glacier characteristics through aerial photography, although land-based measurements (especially newly developed ground penetrating radar) are the most accurate.

Llaca Lake, Huascarán National Park, Peru, is dominated by ice-covered peaks. Large hanging glaciers suspend from the shoulder of the peak on the right (Ranrapalca, 6,162 meters). Flatter, thicker glaciers lie below. As the glacial tongue retreats, it leaves Llaca Lake where the glacier used to be. Large icefalls from the tops of these peaks are capable of reaching the lake. Photo: John Harlin

3.3.2. SLOPE OF THE BEDROCK

Slope is an important factor in determining the potential of avalanche debris falling into glacial lakes. The slope is used in calculating glacier stability and the probability of failure from edge effects or ramp type. Scientists at the University of Zurich have developed empirical relationships based on glacier studies in the Alps that help to determine the slope at which slippage might occur depending on temperature. This relationship allows slope measurements from satellite imagery and digital elevation models to be used in determining the potential of a flood event. For example, a 25-degree gradient might lead to sliding of warm glaciers in Peru, whereas the same gradient might not lead to sliding in the cold environments of high-latitude glaciers. Adhesion of the ice to underlying bedrock is highly dependent on ambient air temperature. Good examples include Case Study 5.1: Lake Palcacocha and Case Study 5.3: Lake 513, both of which have bedrock slopes steeper than 30 degrees.

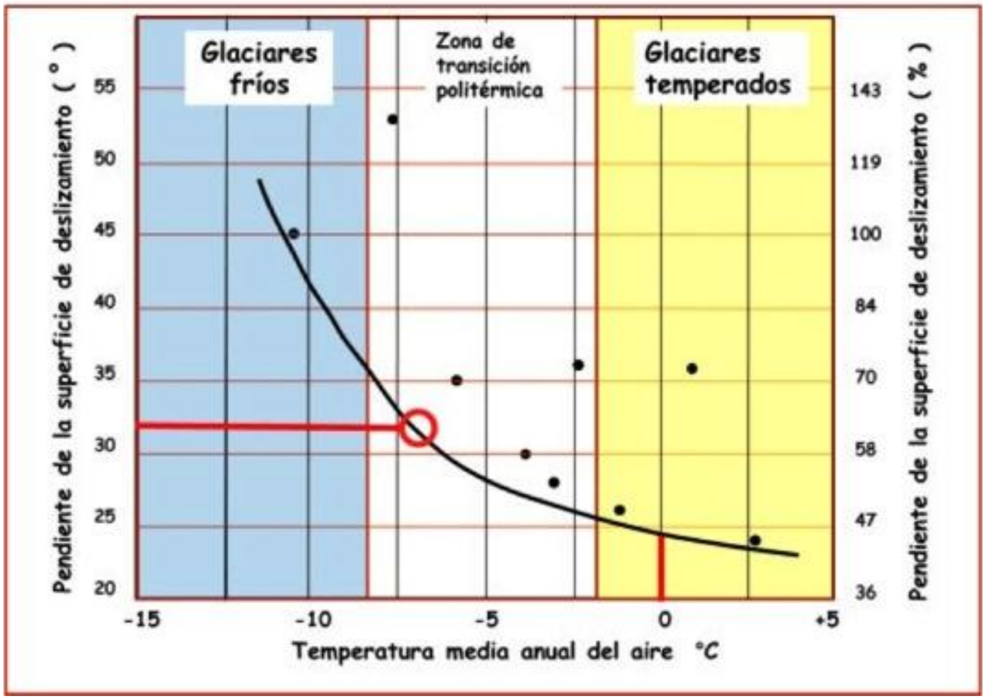


Figure 3-1 Critical Slopes for Different Types of Tropical and High Latitude Glaciers. Vertical axis: Slippage surface gradient. Three categories: cold glaciers, polythermal transition zone, temperate glaciers. Horizontal axis: Average annual air temperature. Source: Institute of Geography of the University of Zurich

3.3.3. GEOMETRY AND STRUCTURE OF MORAINES FORMING THE LAKE BASIN

Considering that many GLOFs result from moraine material sliding into the lake, the composition and slope of the moraine can determine the stability of its basin. For example, the geometry or cross section of a moraine might be either trapezoidal or triangular in shape. A triangular shape is generally less stable and grows weaker as rain and wind gradually erode the moraine's steep slopes. By contrast, a trapezoidal shape generally yields a moraine that's more compact, stable, and not so easily eroded by rain, wind, or other natural processes. Case Study 5.14: Shallap Lake displays a trapezoidal shape and Case Study 5.1: Palcacocha Lake displays a triangular shape.

3.3.4. LENGTH AND SLOPE OF THE DOWNSTREAM VALLEY

When a GLOF occurs, the destruction it will cause downstream strongly depends on its volume and kinetic energy. A flood's kinetic energy will depend on the physical characteristics of the path of the downstream flow. A long path with a gentle slope will dissipate some of the flood's energy, as experienced in the valleys downstream of the Quelccaya Ice Cap in Cusco, Peru. In 2006, a new glacial lake at the terminus of the Qori Kalis Glacier tongue overflowed. Because of the extensive length and gentle gradient of the valley, the flood lost momentum. If it were not for an increased discharge into the Salcca River, communities downstream would have been unaware that a GLOF event had occurred in the upper watershed (Lonnie Thompson, pers. Comm. 2006; Thompson et al., 2011).

By contrast, in October 2010 a small GLOF caused by falling ice at the foot of the Nevado Chicón, in the Cordillera Urubamba (Cusco, Peru), caused significant destruction. The flood's velocity increased as it traveled the steep downstream gradient. Its energy dissipated when the floodwaters reached the Occoruruyoc plain. However, the energy picked up again during the next drop in elevation and the ensuing damage was magnified by construction debris that had been left in the river (see Case Study 5.17: Riticocha Lake).

3.3.5. PRESENCE OF HANGING GLACIERS

Masses of ice on very steep slopes without support from below are termed hanging glaciers. The combined effects of their large volume and gravity can cause huge avalanches that may result in dangerous surges if it falls into a lake. Decreasing adherence between the ice and the basal rock because of warming temperatures, especially in tropical glaciers, creates unstable conditions for glaciers on steep, rocky slopes.

This happened in Case Study 5.3: Lake 513 and in many other glacial lakes where moraine dams were subjected to strong hydrodynamic events. In the Lake 513 example, a mass of ice with an approximate volume of 380,000 m^3 fell toward the lake, carrying with it enough rock to yield a total volume of approximately one million cubic meters. Its impact produced a wave over 20 meters high in a lake of 8 million cubic meters (its depth at the time was 85 meters).

Large hanging glacier over Lazo Huntay Lake in the Cordillera Huaytapallana, in central Peru, 1990. Photo: César Portocarrero

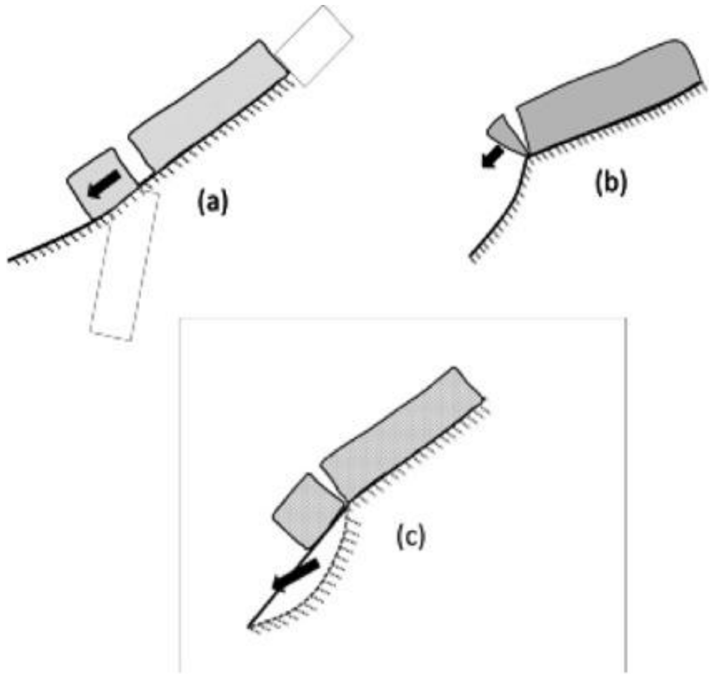


Figure 3-2 Types of Glacial Avalanches. Ramp (a), edge (b), ramp including rock failure (c). Several factors can trigger a hanging glacier to break off and fall directly into the lake, causing a strong hydrodynamic surge in the form of waves. The waves may flow directly over the moraine dam or erode the dam to the point where a complete outburst flood can occur, with serious consequences downstream. Source: Institute of Geography of the University of Zurich

3.3.6. GLACIER TONGUES UNDERMINED BY GLACIAL LAKES (CALVING)

As glaciers retreat, it often leaves behind empty spaces that are gradually filled with meltwater and eventually form lakes. As these lakes are still in direct contact with the glacier tongue, the temperature difference between the water and the glacier produces an eroding effect that eventually causes the ice to break off and cascade into the lake. This can create a dangerous surge wave, depending on the mass of the ice and the volume and shape of the lake. This phenomenon has caused natural disasters in many places. Examples include the event in Case Study 5.1: Palcacocha Lake, which flooded the city of Huaraz. Also in Case Study 5.16: Lazo Huntay Lake, which flooded the town of Huancayo, and, more recently, in an unnamed lake at the foot of the Nevado Chicón (see Case Study 5.17: Riticocha Lake).

Pastoruri Glacier, Peru, in contact with an emerging lake, showing the calving process. Photos: César Portocarrero (left), Daene McKinney (right)

3.3.7. VOLUME OF THE LAKE

A seismic event, an avalanche, the collapse of a glacier, a slide of the lake basin itself, or other factors can create surge waves and other disturbances that trigger outburst floods. The magnitude and destructive potential of the flood depends in part on the volume of the lake. Decades of preventive work in Peru have revealed that the most effective preventive measure is to reduce the volume of dangerous lakes. This approach is used in nearly all the case studies in this report.

3.3.8. SEISMIC AND TECTONIC FACTORS

Although the relationship between seismic activity and glacier stability is unclear, the example of Case Study 5.16: Lazo Huntay and Chuspicocha Lake, which flooded the town of Huancayo in central Peru, demonstrates that earthquakes can result in glacial avalanches. In 1969, seismic activity along the Huaytapallana fault caused large fragments of ice to fall into Lazo Huntay Lake, breaking the stone and mortar artificial dam that was used for water storage. Another example is Case Study 5.10: Llanganuco Lakes, which was impounded by avalanches triggered by a magnitude 7.9 earthquake in 1970. The most devastating consequence of the 1970 earthquake was a massive icefall from Huascarán Norte (estimated volume is between 50 and 100 million m^3). The avalanche's trigger was likely falling rock from Nevado Huascarán Norte that dragged the overlying glacier with it. Though it did not strike a lake, the ice liquefied during its descent, creating a massive debris flow that flooded the town of Yungay, killing approximately 6,000 people (Evans, et al. 2009).

3.3.9. DISCHARGE RATES

Engineers and decision makers must know the magnitude and variation of discharge rates from a glacial lake to properly design pipelines and overflow sluices that can prevent the lake's surface from rising to unsafe levels. These measurements should determine a value where water can be transported easily through the pipeline even during periods of heavy rainfall and sudden inflows into the lake. These sorts of data were used for the detailed hydraulic designs of all projects mentioned in this report. Case Study 5.9: Jatuncocha Lake is an example of this challenge; its pipes that were barely large enough for an event that occurred half a century after installation.

3.3.10. DETERMINING THE POTENTIAL GLOF TRIGGER

All glacial lake outburst flood (GLOF) occurrences are triggered by a variety of locally-specific variables. Contributing factors include lake volume, large impacts from above (rock or icefall), and moraine collapse due to its shape or internal weaknesses. Complicating the identification and monitoring of a GLOF is that these factors often change over time. Thus, understanding potential triggers for each lake is critical to evaluating risk. Potential triggers can be surmised based on history, statistics, or models; however, field verification is critical to their determination. Each case study in this report examines the past and potential triggers for that particular lake.

3.4. MORAINES AND ITS STRUCTURE

Understanding the formation of glacial lakes requires understanding how glaciers move and create moraines. The precursor to a glacier is a mass of ice that has accumulated over decades or centuries. When the weight, slope, and other conditions are sufficient to overcome friction, the ice begins sliding down the mountain slope. This moving ice is a glacier. Acting as a natural bulldozer and conveyor belt, the ice carries with it all loose material in its path. This downward movement and transport of material leads to the formation of moraines, which are the accumulations of material eroded by glaciers and dropped at their edges (both terminal and lateral). Moraines have a heterogeneous structure because glaciers transport everything in their path (sometimes over many kilometers) in addition to whatever falls onto their surfaces from the mountains above.

A typical moraine includes fine sediment such as clay, silt, and sand; coarse sediment such as gravel and coarse sand; and much larger material including rocks and boulders of varying dimensions. In many cases this sediment is highly compacted, with a high mechanical resistance and sealing properties. Such moraines often have steep gradients.

This morainic material forms natural dams across narrow mountain valleys. In cases where the sediment is tightly compacted and cohesive, the dammed basin becomes an excellent container for water storage. These natural dams are weaker where the moraine is composed of non-cohesive sandy sediment or sandy silt mixed with non-cohesive fine sediment.

As glaciers melt and recede, the space it once occupied is often replaced by glacial lakes of varied dimensions. The diverse morphologies of this terrain, in terms of shape and gradient, are one of the risk factors associated with glacial lake evolution. Risk increases with growth of water volume in the lakes, retreat of glacier termini, weak moraine layers, moraine erosion, potential piping or pothole erosion, seepage, the presence of hanging ice that can fall into the lake, the potential for landslides to hit the lake, and seismic activity.

The terminal and lateral moraines that contain Palcacocha Lake, showing the 1941 breach that released a GLOF that devastated the city of Huaraz. Photo taken in 2013. Photo: John Harlin

Glaciofluvial material, like moraines, is composed of angular boulders and gravels, clay, and sand in a mix of varying proportions. Each layer can exhibit a certain degree of local homogeneity, but the composition changes greatly between layers, as do physical characteristics such as resistance to erosion, cohesion, and angle of internal friction. All of these factors affect the stability of a moraine and the debris content of a glacial lake outburst flood.

GLOFs can be triggered by many things, including an earthquake, the slipping of the inner morainic wall of a lake, piping, seepage, and rock or ice avalanches into a lake. Whatever the trigger, a large-scale outburst flood typically begins with a rupture in the moraine that leads to a violent flood that transports morainal material mixed with water and ice downstream. Large water volumes and steep gradients allow the flood-transport of heavy rocky material, leading to the formation of large glaciofluvial deposits hundreds of meters or even kilometers from the source.

Finer eroded sediment is carried over much longer distances or by more gently sloping rivers. Floods resulting from a breached dam can lead to sedimentation and damming downstream, where deposition of silt or other fine sediment in horizontal layers can form temporary ponds along the main river channel.

Outburst floods and avalanches have caused the majority of natural disasters in the Cordillera Blanca, making research and assessments of these events extremely important. Knowledge of the conditions that cause these events and their characteristics can provide insight for future preventive measures.

3.5. PROCESS LEADING TO GLACIAL RUPTURE AND POTENTIAL ICE AVALANCHES

As glaciers move they crack and sometimes rupture because of friction, bending, and other causes. Cold-based glaciers—where ground temperatures are below the pressure-melting point and the glaciers are well adhered to the bedrock—rupture directly in the ice itself prior to any ruptures at the base resulting from friction contact with the ground. However, in warm-based glaciers, also known as temperate glaciers—where ground temperatures are close to the pressure-melting point—friction plays an important role as the ice slides over the bedrock surface. Cordillera Blanca glaciers are temperate (Kaser et al., 2002).

As ground slippage increases, the following can occur:

- Cavitation can occur where friction diminishes and velocity of slippage increases. This phenomenon can increase until it produces an avalanche.
- Cavitation does not occur, even as friction increases with velocity. This leads to a dynamic equilibrium with no rupture and no avalanche.
- Meltwater can accumulate between the ice and the bedrock. This decreases contact-resistance between the two surfaces (i.e., lubrication), which can result in increased slippage.
- Changes in air temperature can affect glacial movements. Sharp surges can result from increased temperatures at the interface between glaciers and the underlying bedrock.

Equilibrium in a glacier depends, among other things, on accumulation and ablation. An excess of accumulation increases its weight, which can lead to a glacier surge that changes the glacier's geometric characteristics (thickness, slope). A rapid increase in thickness can break equilibrium and cause a significant downhill surge.

3.6. SOCIAL POLICY CONSIDERATIONS IN GLACIAL LAKE MANAGEMENT

Disaster risk management needs to fit into overall development planning to ensure that efforts are sustainable for the long run. This affects not only the technologies used for managing the lakes, but also whether and how these lakes are utilized to support a region's water management planning. Water resources today are being seriously affected by climate change in many regions due to reduced glacial volume available for meltwater and shifting precipitation patterns (Baraer, et. al, 2012). At the same time, increasing populations and spreading development require dependable water sources. In contrast to Peru's early history of glacial lake management—when the only concern was for the safety of populations downstream from glaciers and dangerous lakes—policy makers today need to preserve water resources for diverse communities. Conflicts over water use have already led to social strife in the Cordillera Blanca (see Case Study 5.2: Parón Lake).

Left: Nevado Huascarán in May 1970 after a 7.9 magnitude earthquake triggered a massive avalanche from the north peak that turned into a debris flood. Approximately 6,000 people are believed to have died in the flood. Photo: Walter Welch. Right: A Google Earth view of Yungay and Huascarán in 2013. Many homes have been built on the debris of the 1970 flood.

Policy makers must also take into account the human tendency to discount future risks in the face of immediate needs. Despite Peru's history with flooding from glacial lake outbursts—as evidenced by written records in the past three centuries and by geomorphological evidence prior to that—communities typically rebuild in almost the exact locations that were previously devastated (Carey, 2010). This is largely because of socioeconomic conditions that make relocation to safer areas difficult. Social policies for downstream populations are outside the scope of this report, but they are nevertheless urgent priorities for civic leaders.

3.7. METHODOLOGY FOR REDUCING THE RISK FROM DANGEROUS GLACIAL LAKES

The Glaciology Unit of Peru's National Water Authority (ANA) developed the following methodology as its standard process for basic research, diagnoses, and treatment of potentially dangerous glacial lakes:

Basic research:

- Create an inventory of glacial lakes.
- Carry out an initial assessment of lake characteristics including surrounding glaciers. This assessment includes topography, basic geology, basic glaciology, and profile analysis in cases where ice is in contact with or could be inside the moraines.

Diagnosis:

- If the initial assessment finds characteristics that indicate downstream risks, further study is warranted. This includes cartographic and bathymetric studies of the glacial lake and surrounding terrain, glaciological studies of all snow and ice that could affect the lake, geological studies, and analyses of soil mechanics. These studies should begin to address potential safety measures.
- Analyze the hydrology of the watershed. This determines safe discharge levels for the design of overflow canals, allowing for safe removal of excess lake volume. Wherever feasible, safety efforts should be combined with water development projects for lakes. This allows hazard mitigation to go hand in hand with resource management.

Treatment:

- Establish logistical access. The distance that tools, construction materials, food, and other supplies must travel (especially by foot, horse, or helicopter) is an important element in cost analysis and time planning.
- Implement safety measures based on information collected from the in-depth studies. Safety measures include volume reductions, hydraulic infrastructure such as open canals, and drainage tunnels or channels that will be covered by a rebuilt dam to contain potential surges caused by falling ice.
  - In most cases, the theoretical best solution would be to completely empty the threatening lake. However, this is typically very expensive, especially in a remote location. Thus, for practical reasons, one must look for intermediate solutions that eliminate most of the threat at an affordable cost.
  - The most common methods for reducing lake volume in Peru have been:
    - Cutting the downstream face of the moraine into a V shape. This measure is commonly implemented in glacial lakes with moraine dams. The cutting process will gradually lower the water level. However, if an avalanche strikes the lake during construction, the moraine is in a highly compromised position. Therefore, lake levels should first be lowered by pumping or siphoning prior to the process of cutting into the moraine. This creates a rim (freeboard) that can buffer potential surges during construction.
    - After the opening has been cut, a reinforced concrete pipe of appropriate diameter for the correct drainage is installed to maintain the reduced lake level. An earth dam with a stone façade is then built over the pipes, restoring much of the original V-shaped cut in the moraine. This dam protects against the hydrodynamic effects of big waves.
    - Construction of drainage tunnels. Drainage tunnels can be drilled into glacial lakes that have natural rock dams and, in some cases, also into lakes with loose moraine dams. Several procedures have been used to construct these tunnels, and the connection to the lake has varied from case to case.
    - Filtration. Filtration (seepage) has also been used in very permeable terminal moraine dams. It is a simple procedure to open a trench and allow water to leak through the porous material, as was done with Lake Yanarraju in the eastern region of the Cordillera Blanca (the work was directed by the author but is not a case study in this report).
- Maintain the highest standards in construction. Peru's experience is that sometimes the safety infrastructure is not put to the test until many decades after its construction. This highlights the need for following sound engineering standards that will maintain effectiveness for decades.

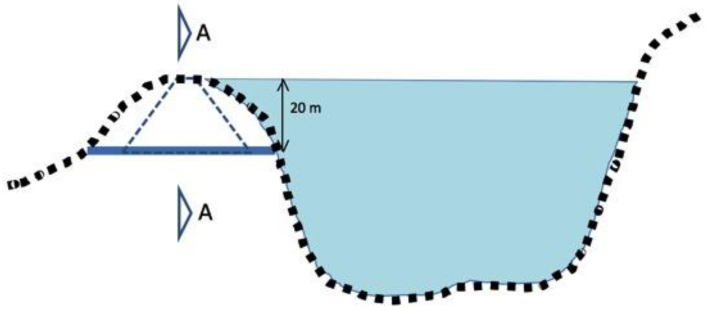


Figure 3-3 Diagram of the Excavation Process to Lower Water Levels of Glacial Lakes Held by Moraine Dams or Other Loose Debris. Diagram by César Portocarrero

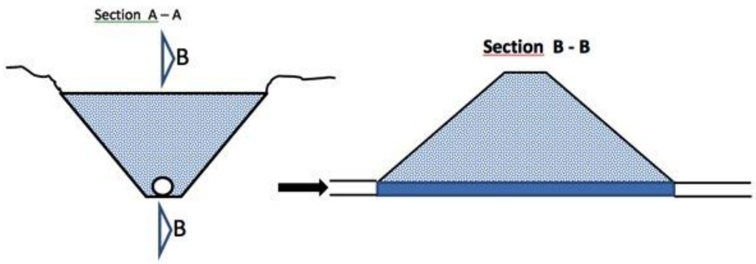


Figure 3-4 Cross Section Showing the Characteristics of the Spillway (left) and a lateral view of the canal showing the restored security dam that will contain surges resulting from falling ice (right). Diagrams by César Portocarrero

4. GEOLOGICAL AND HISTORICAL BACKGROUND TO CASE STUDIES IN CORDILLERA BLANCA

This section provides background information on geography, geology, and historical flooding specific to Peru's Cordillera Blanca. It will be useful for understanding the history and context of the case studies and as a baseline comparison for engineers and policy makers working in other mountain ranges worldwide.

The Cordillera Blanca is in the department (state) of Ancash, Peru.

4.1. OVERVIEW OF THE CORDILLERA BLANCA AND THE CALLEJÓN DE HUAYLAS

The Cordillera Blanca, in Peru's Ancash region, frames the eastern horizon of the Río Santa valley from the Santa River's source at Aguascocha Lake to the range's northern limit at Nevado Champará. While Peru contains 19 snowcapped mountain ranges, the Cordillera Blanca includes the highest peaks and holds 35 percent of Peru's glaciers (Hidrandina, 1988).

The valley called Callejón de Huaylas (Huaylas Valley) is located on the western slopes of the Cordillera Blanca and is home to several major towns including Huaraz, the capital city of Ancash (2007 census population: 100,000). The eastern watershed is less populated, but also affected by glacial lake outburst floods.

The spectacular Cordillera Blanca has attracted high-profile international climbing expeditions since the 1920s. Less famous than the snowy summits are the range's many dangerous glacier lakes. Though there is considerable historical evidence of past flooding, the largest modern event occurred on 13 December 1941, when a moraine dam burst from a surge wave created by an avalanche, launched a wall of water that flooded the city of Huaraz, and killed approximately 5,000 inhabitants (Carey, 2010). Worse yet was a 1970 flood that destroyed most of the town of Yungay, killing 6,000 people (Evans et al., 2009). (Note: most historical accounts place the death toll between 10,000 and 30,000; however, Evans' careful re-examination concludes these numbers were exaggerated.)

Major alluvial phenomena over the past several thousand years in the Cordillera Blanca left clear traces in various watersheds. The subsoil of much of the town of Caraz is comprised of varying-sized boulders and materials that were transported during a debris flow. Although the undated event may have happened long ago, it lingers in cultural memory. Similar events have destroyed other infrastructure, people, and towns. Several of these occurred between the two watersheds on either side of the Cordillera Blanca.

4.2. BASIC GEOLOGY AND GLACIAL HISTORY OF THE CORDILLERA BLANCA

The Callejón de Huaylas runs south-southeast to north-northwest and is flanked by the Cordillera Blanca (White Range) to the east and the Cordillera Negra (Black Range) to the west. The Cordillera Blanca, named for its ice-covered peaks, is a large mass of plutonic rock composed mainly of granodioritic rock, sandstone, shale, and slate. With a high point of 6,768 meters, it is the highest range in Peru and the most glaciated range in the tropics. The Cordillera Negra is mostly volcanic rock. Sitting in the rainshadow of the Cordillera Blanca, the Negra gets little precipitation and has no glaciers despite its high point of 5,430 meters. The Callejón de Huaylas between these high ranges is covered with glaciofluvial, glacial, and alluvial material, separated by outcrops of volcanic rock.

Looking east into the Quilcay watershed from above Huaraz. Photo: John Harlin

Local geological formations in the Cordillera Blanca consist of four primary types:

- Granodiorite is the base rock of the Cordillera Blanca.
- Rocks formed by shales and fine sandstones of considerable thickness with a good degree of settling in the Chicama Formation. This formation is found mostly in some glacial cirques and fluvioglacial deposits.
- Quartzitic rocks, sandstones, and shales with coal seams, in the Chimu Formation. Boulders of detrital material from this formation are found in some gorges.
- Sandstones and shales with thin layers of brown quartzite interleaved with limestone and gypsum. This type of formation is mostly found in the Carhuaz province.

The original morphology of the valley corresponds with the end of the Tertiary and beginning of the Quaternary periods, placing the formation of the low-sloping and low elevation valley at approximately seven million years ago. The later intrusion of the granodioritic batholith from the Cordillera Blanca raised the elevation of the valley by more than 2,000 meters, shearing the western flank and revealing multiple transverse faults.

Increased erosion resulting from the raising event led to the formation of side canyons and gorges. Successive glaciations later played an important role in the geomorphology of the region. Current research indicates that seven glaciations have occurred over the last 650,000 to 680,000 years, with the last major cooling event peaking 18,000 years ago (on average) known as the Last Glacial Maximum (LGM), leading to an interglacial period that lasted for approximately 6,000 years (Benn and Evans, 1998; Dexter et al., 2013; IPCC, 2013). From this time forward higher temperatures and decreased snowfall resulted in gradual ice melt and glacial recession with the exception of a minor cooling event known as the Little Ice Age, which occurred between the years 1450 and 1850. Evidence of the Little Ice Age in the Cordillera Blanca is easily seen in the small moraines near today's glaciers.

Lower elevations display a high degree of heterogeneity of detrital rock deposits and irregular shapes from the underlying volcanic processes. These have created a unique morphology for the banks of the Río Santa characterized by soft undulations abruptly cut by areas of sheet erosion, characteristics that are often confused with landslides.

4.3. PRIMARY NATURAL DISASTERS IN PERU

Peru has a long and fairly well documented history of natural disasters. It is probable that significant glacial retreats during the medieval warming period (800 to 1200 A.D.) also produced avalanches and floods whose traces are visible on many slopes around the Cordillera Blanca, including Caraz, Marcará, and the Callejón de Huaylas.

Historical studies of glacial flood events need to be updated. In the 1960s, glacial studies focused mostly on physical characteristics and transformation processes. Current research is more oriented toward changes in glacial mass and the impacts of climate change. Temporal analysis of glacial volumetric variance currently includes photographic comparisons, satellite imagery, topographic measurements, and other modern techniques. These are important in determining how shrinking glaciers affect water availability.

GLOFs are not the only events that produce mass flow movements in mountain streams. Floods can also result from prolonged periods of heavy rain that cause solifluction (soil movement) phenomena—for example, the huge flood at the Machu Picchu Hydropower Plant near Cusco, Peru, in February 1998 (Portocarrero, 1998). Violent lake outbursts may also occur as a consequence of human intervention to build safety works, as happened in the Cordillera Blanca on Case Study 5.5: Jancarurish Lake in 1950. Construction of an open pit canal can cause a violent outburst of lake water if an ice avalanche on the lake or any of the other trigger events occurs during construction. At present, the likelihood of avalanches is increasing because of the effect of global warming on glaciers, which are losing their adherence to the bedrock (Cochachin, 2013).

Table 1 Flood Events in Peruvian Glaciated Moutains. (Source: recent events and historical reports come from the Unidad de Glaciología y Recursos Hídricos (Glaciology and Water Resources Unit) of Peru's National Water Authority. The organization is generally referred to as the "Glaciology Unit" in this document, though it has had various names and responsibilities and has existed under different authorities, as described in 1.2.)

Flood Events in Peruvian Glaciated Mountains	
Year	Event
1725	Avalanches and outburst floods in Huaraz
1883	Outburst flood in Macashca, close to Huaraz
1869	Outburst flood in Monterrey –- Huaraz
1917	Outburst flood from Nevado Huascarán over RanrahircaRanrahírca
1938	Outburst flood in the Ulta –- Carhuaz ravine
1941	Outburst flood in Pativilca watershed
1941	Outburst flood in Huaraz (4,000 dead)
1945	Outburst flood over the Chavín de Huantar ruins
1950	Outburst flood in Jancarurish reservoir. Hydropower plant destroyed
1951	First outburst flood from Artesoncocha Lake – Parón Lake
1951	Second outburst flood from Artesoncocha Lake – Parón Lake
1952	Outburst flood from Millhuacocha Lake – Quebrada Ishinca
1953, 1959	Outburst flood from Tullparaju Lake – Huaraz
1962	Outburst flood in Ranrahirca, Nevado Huascarán (1,000 dead)
1965	Outburst flood in the Tumarina Lagoon – Carhuascancha
1989	Outburst flood in Huancayo, from an outburst of Chuspicocha Lake
1970	Outburst flood in Yungay and Ranrahirca (6,000 dead)
1998	Outburst flood in Machu Picchu. Hydropower plant destroyed
2003	Palcacocha Lake overflows with ice; mostly contained
2010	Outburst flood at Lake 513. Large torrent, some property damage
2010	Outburst flood from Riticocha Lake in Urubamba
2012	Artizon Lake GLOF destroyed popular trekking trail

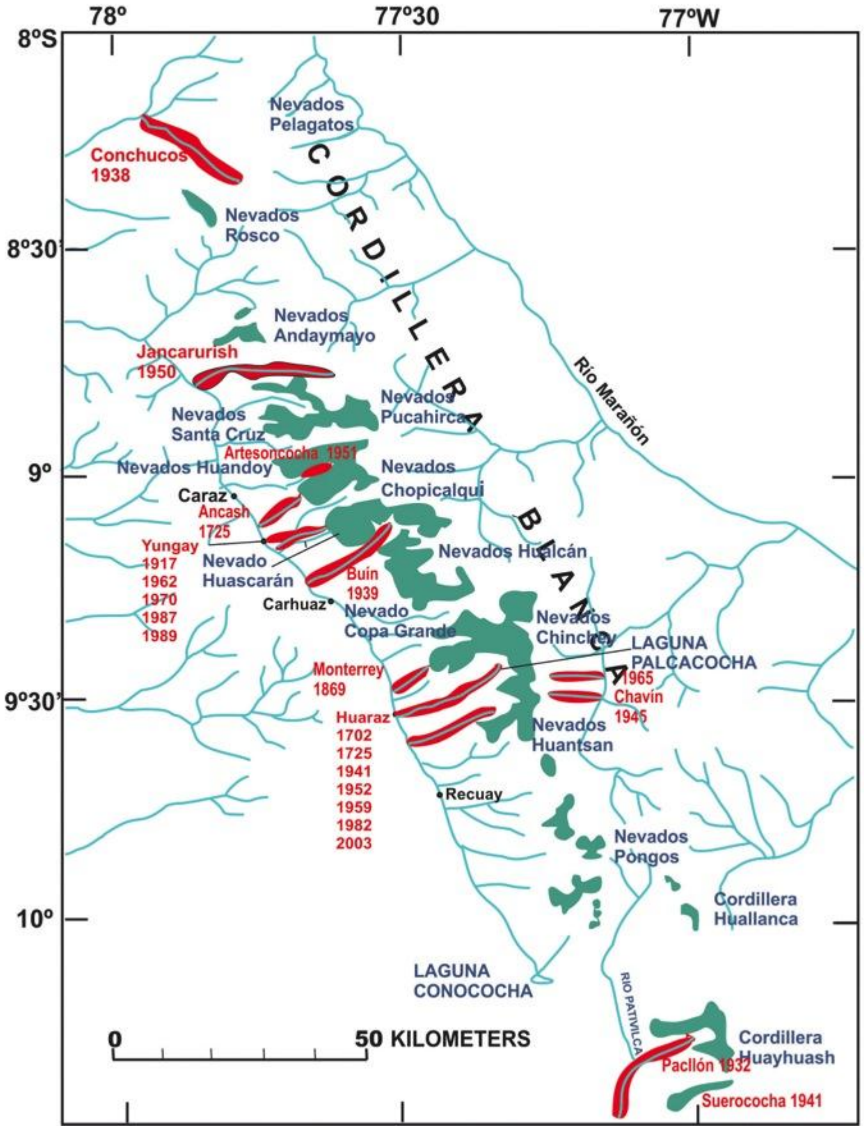


Figure 4-1 Location of Natural Disasters in the Cordillera Blanca. Source: USGS

4.4. GLACIAL LAKES IN THE CORDILLERA BLANCA

An updated inventory (Glaciology Unit, 2009) indicates there are 830 glacial lakes in the Cordillera Blanca, with 514 draining into the Río Santa watershed and on to the Pacific Ocean (the east side of the Cordillera Blanca drains to the Atlantic). All 514 have surface areas greater than 5,000 m^2 and volumes between 100,000 m^3 and 79 million m^3.

Five of these glacial lakes have caused natural disasters in the past. Several may pose significant current threats. Over the past three decades, increased climate variability has reduced glacier stability and created conditions different from those studied prior to the 1970s. Prevention measures need to include new criteria such as water management (smaller glaciers contribute to increased stress on water supplies) and disaster risk analyses (warmer temperatures can lead to increased frequency of ice avalanches).

Pragmatism has directed Peruvian efforts during the past 70 years toward one standard safety measure: lake volume reduction. Reducing the volume of a glacial lake is a less radical and more practical solution than complete lake drainage, which proved to be extremely expensive.

The process of reducing lake volumes has improved over the decades because of an increase in financial resources and new technology, including mechanical equipment. In the present context of climate change and its impact on water resources, treating dangerous lakes also needs to take into account water resource management.

5. CASE STUDIES FROM PERU

This section describes 17 case studies from Peru's history of glacial lake management, mostly in the Cordillera Blanca. The case studies are presented from the perspective of this report's lead author, who was personally involved with the mitigation efforts on these lakes while working as a civil engineer for the Glaciology Unit from 1973 to 1996 (he also consulted on the emerging lake in Urubamba, 2012). Some of the case studies are presented in considerable detail; others much less so. Such details are intended as background information to demonstrate the complexities sometimes encountered in managing glacial lakes. While the precise details are not universal, similar challenges can emerge anywhere. Some of the following descriptions will serve as cautionary examples.

The case studies are presented with the more detailed cases from the Cordillera Blanca coming first, followed by several less detailed case studies, and concluding with an emerging case from the Cordillera Urubamba near Cuzco, in southern Peru.

Safety measures adopted for glacial lakes in the Cordillera Blanca rely on three primary steps: (a) decreasing lake volume, (b) building drainage systems that maintain the volume at desirable levels, and (c) building reinforced dams that can contain or withstand tall waves resulting from falling rock or ice. These three steps were followed in nearly all of the following examples.

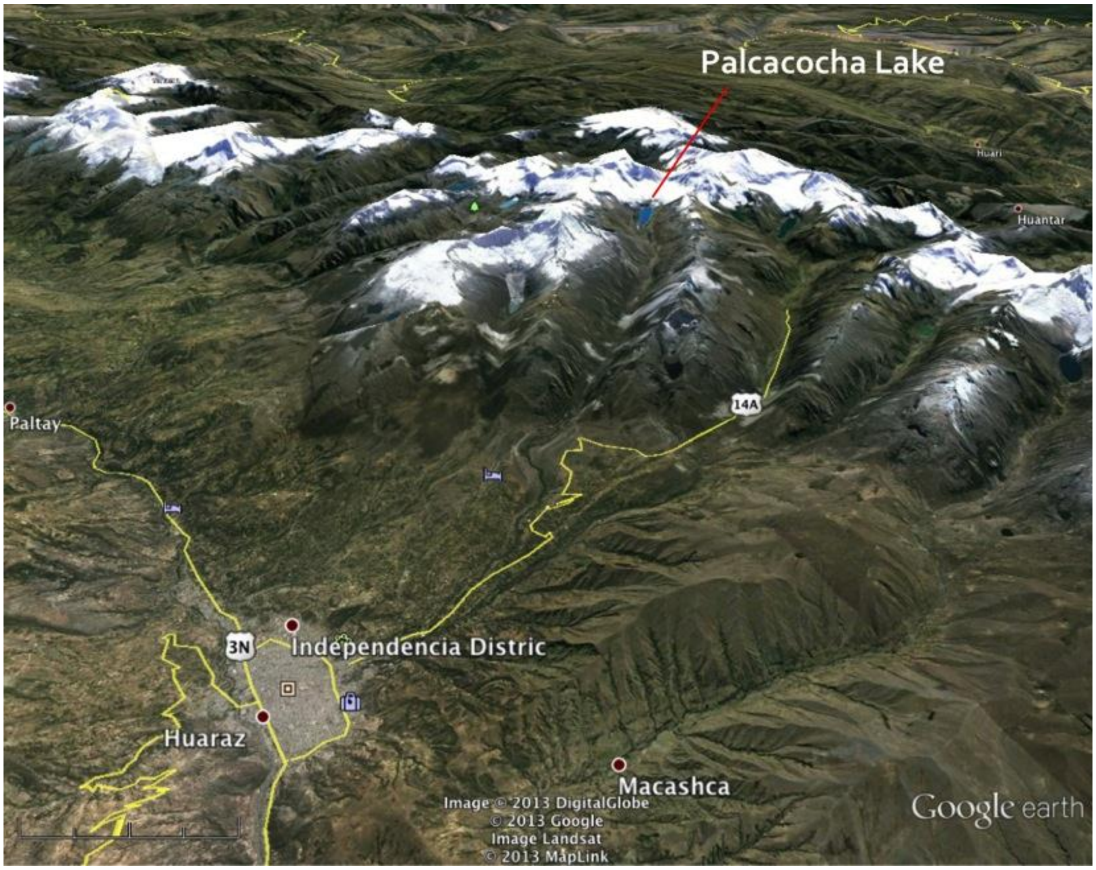
Table 2 Thirty Five Glacial Lakes in the Cordillera Blanca with Installed Safety Features. To find these lakes, enter their coordinates into Google Earth. Source: Unidad de Glaciología y Recursos Hídricos, Peru (Glaciology and Water Resources Unit). Updated in 2011.

35 Glacial Lakes in the Cordillera Blanca with Installed Safety Features								
No.	Name	Coordinates (WGS84-DD)		Present Characteristics				Date (Bathy-metry)
		Lat. (Dec. Deg.)	Long. (Dec. Deg.)	Altitude (MASL)	Area (m)	Volume (m)	Depth (m)	
1	Safuna Alta	-8.8390135	-77.619917	4360	334359	15524434	84	2010
2	Pucacocha	-8.8564398	-77.632105	4494	277201	8463000	79	2006
3	Llullacocha	-8.8556823	-77.642139	-	-	-	-	-
4	Cullicocha	-8.8648486	-77.759092	-	-	-	-	-
5	Yuraccocha	-8.8842925	-77.735752	4618	287269	8177746	55	2011
6	Taullicocha	-8.9057257	-77.587823	4426	133766	2448918	64	2007
7	Jatuncocha	-8.929594	-77.663923	3886	486551	9233206	34	2007
8	Arhuaycocha	-8.8865196	-77.627141	4400	398824	19550795	98	2011
9	Parón	-8.99985	-77068464	4174	1480489	39888953	43	2007
10	Huandoy	-9.0125027	-77.678062	4740	7718	16722	5	2007
11	Llanganuco Alta	-9.0654701	-77.085603	3833	684199	2018264	10	2007

35 Glacial Lakes in the Cordillera Blanca with Installed Safety Features								
12	Llanganuco Baja	-9.0738955	-77.64889	3820	579950	11747150	29	2007
13	Lake 69	-9.012066	-77.609364	4604	97800	2763009	58	2009
14	Artesa	-9.1140182	-77.516023	4286	22797	124743	12	2005
15	Huallcacocha	-9.1609571	-77.547971	4355	163067	4664724	76	2005
16	Cocha	-9.2163655	-77.543311	4538	69205	1001230	27	2007
17	Rajupaquinan	-9.2232643	-77.55422	4150	35438	462407	27	2007
18	Lake 513	-9.2135951	-77.551704	4431	207585	9250938	83	2011
19	Lejiacocha	-9.2701218	-77.507693	4618	183907	1356126	20	2005
20	Paccharruri	-9.2859621	-77.451858	4462	278053	7134636	50	2005
21	Pucaranracocha	-9.3339847	-77.344726	4390	234622	4398308	46	2007
22	Akillpo	-9.3390165	-77.421857	4704	412463	3896312	32	2004
23	Pacliash Cocha	-9.3365171	-77.364907	4564	218679	2451103	26	2010
24	Ishinca	-9.3870721	-77.418522	4960	87902	785872	25	2004
25	Pacliash	-9.3712415	-77.410186	4577	188873	3985344	42	2011
26	Mullaca	-9.4332222	-77477391	4596	110695	2043738	38	2006
27	Llaca	-9.4370732	-77.444918	4474	43988	274305	17	2004
28	Palcacocha	-9.93981806	-77.381023	4562	518426	17325207	73	2009
29	Cuchillacocha	-9.4106814	-77.353796	4620	145732	2138936	27	2005
30	Tullparraju	-9.4215155	-77.343248	4283	463757	12474812	64	2011
31	Cayesh	-9.459846	-77.332129	-	-	-	-	-
32	Shallap	-9.4929029	-77.356858	4260	165251	3467585	37	2004
33	Rajucolta	-9.5233981	-77.343083	4273	512723	17546151	73	2004
34	Yanaraju	-9.1333716	-77.483678	4142	229707	7642096	61	2005
35	Allicocha	-9.2461804	-77.455903	4543	357518	5698019	33	2006

5.1. PALCACOCHA LAKE

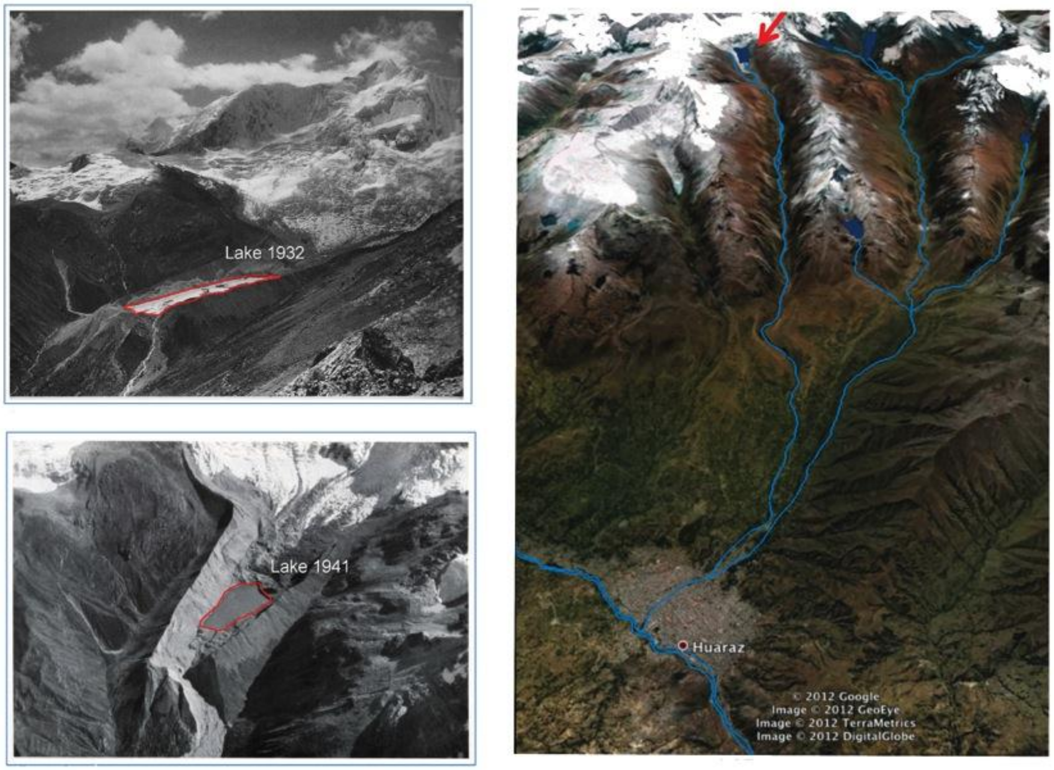
Location: 4,562 meters, northeast of the city of Huaraz, at the head of the Quebrada Cojup. Palcacocha drains into the Paria River, which soon converges with the Auqui River to form the Quilcay River that runs through the city of Huaraz on its way to the much larger Santa River in the valley bottom (all in a distance of about 30 kilometers).



Palcacocha Lake in 2013 and the valley it flooded during the GLOF that destroyed much of the city of Huaraz (lower left) in 1941.

Risk: The lake's volume is 34 times greater now than it was in 1970 (described below), making it a continued threat. The population of the city of Huaraz has grown from 25,000 in 1941 (when 5,000 people were killed by a GLOF from Palcacocha) to 100,000 in 2007 according to the census (many of whom currently live in rebuilt structures in the 1941 floodplain). In March 2003 there was a small overflow of Palcacocha, but no serious damage occurred in Huaraz.

History of work: In the late 1930s, the Austrian Hans Kinzl surveyed in the Cordillera Blanca, during which he photographed Palcacocha Lake. He warned the citizens of Huaraz that Palcacocha's moraine could rupture, which would produce a highly destructive flash flood. His warning was ignored. On 13 December 1941, an icefall from the mountain above struck the lake, launching a wave that washed over the moraine. The moraine collapsed and the ensuing flood destroyed a third of the city of Huaraz, killing 5,000 people. Ensuing engineering projects to build security systems for Palcacocha Lake launched the modern era of glacial lake management in Peru.



Palcacocha Lake in 1943 before the GLOF (top) and after. Right: The red arrow points to Lake Palcacocha in 2012; blue lines are streams leading from several glacial lakes into Huaraz. Top photo: Hans Kinzl. Bottom photo: Servicio Aerofotográfico Nacional del Perú (Peru's National Aerial Photography Service)

The GLOF's destructive path through the city of Huaraz in 1941. Servicio Aerofotográfico Nacional del Perú

Many factors contributed to the 1941 catastrophe, including the lack of a road to the lake, which meant that few people witnessed the growing danger. There was also a general ignorance at the time of glacial phenomena. This lack of awareness included all levels of Peruvian society, from academia, engineers, government, and scientists. No one monitored glaciers and glacial lakes.

Ten years later, the Peruvian government launched the Control Commission of Cordillera Blanca Lakes, charged with monitoring glacial lakes and developing mitigation options for those they declared dangerous.

In an effort to mitigate the risk of the lake, two 36 inches (915 millimeters) steel pipes were placed in the notch that had been cut into the moraine by the GLOF. Then, an 8-meter rammed earth dam was built over the top. These safety works continued working properly until the May 31, 1970, earthquake (magnitude 7.9) destroyed the dam's foundations, breaking the drainpipes installed underneath.

At that time the Lakes Safety and Glaciology Unit decided to lower the lake's level by one meter, which they concluded was enough based on its low volume of 500,000 m^3. In 1974, they installed a 48 inches (1,219 millimeters) diameter steel pipe capped by a new, tightly compacted dirt dam 8 meters high. They also strengthened the right side of the moraine outflow to reduce erosion from outbursts. This provided a freeboard of 8 meters in the lake as a buffer against future surge waves.

Nineteen years later, in March 2003, the moraine along the lake's left flank slipped, launching a violent diagonal wave that traversed the lake and heavily eroded the reinforced dam. Photographs, taken five days after the 2003 event, show chunks of ice still sitting on the 8-meter dam, and water levels still 4 meters above its normal level. This event frightened the Huaraz city authorities. The regional government quickly repaired the damaged structures.

The safety dam on Palcacocha Lake as construction was being completed in 1974 (left) and with ice debris following the 2003 landslide that launched a flood that was mostly contained by the dam. Left photo: César Portocarrero. Right: Glaciology Unit Office Archives

Following the March 2003 event, the Natural Resources Management Office conducted a bathymetric survey and determined the lake had a volume of 3.8 million cubic meters. This was used as the defining figure until April 2009 when a more thorough bathymetry revealed the volume to be 17 million cubic meters—more than four times greater. The Glaciology Unit advised new safety works, considering that the lake's volume had increased from half a million cubic meters in 1974 to 17 million in 2009.

The Glaciology and Water Resources Unit prepared a plan in 2010 to lower the water level of Palcacocha Lake by an additional 15 meters. The cost estimate for this work came in at US$4 million. Later in 2010, Peru's National Water Authority unexpectedly relieved the Glaciology and Water Resources Unit from responsibility for glacial lakes and turned the lake-lowering plan over to the regional government in Ancash. Ancash officials did not think they could authorize these funds quickly, so they searched for an interim, cheaper way to reduce risk from the lake. They decided to use six 10-inch(254 millimeters)-diameter pipes about 700 meters long to siphon off approximately 7 million cubic meters of water. Two years later (in 2011), the siphons started draining the lake though at a slower rate than planned due to design defects. As of July 2013, the water level had been lowered approximately 3 meters, roughly half the amount needed before the drainage ditch can be started.

Palcacocha Lake in 2013 showing the siphon pipes entering (left) and exiting the tunnel under the dam. Photos: John Harlin

The future plan for Palcacocha Lake is to lower it by an additional 15 meters over time. Once lowered, a permanent drainage system and dam will be installed.

Table 3 Palcacocha Lake Characteristics

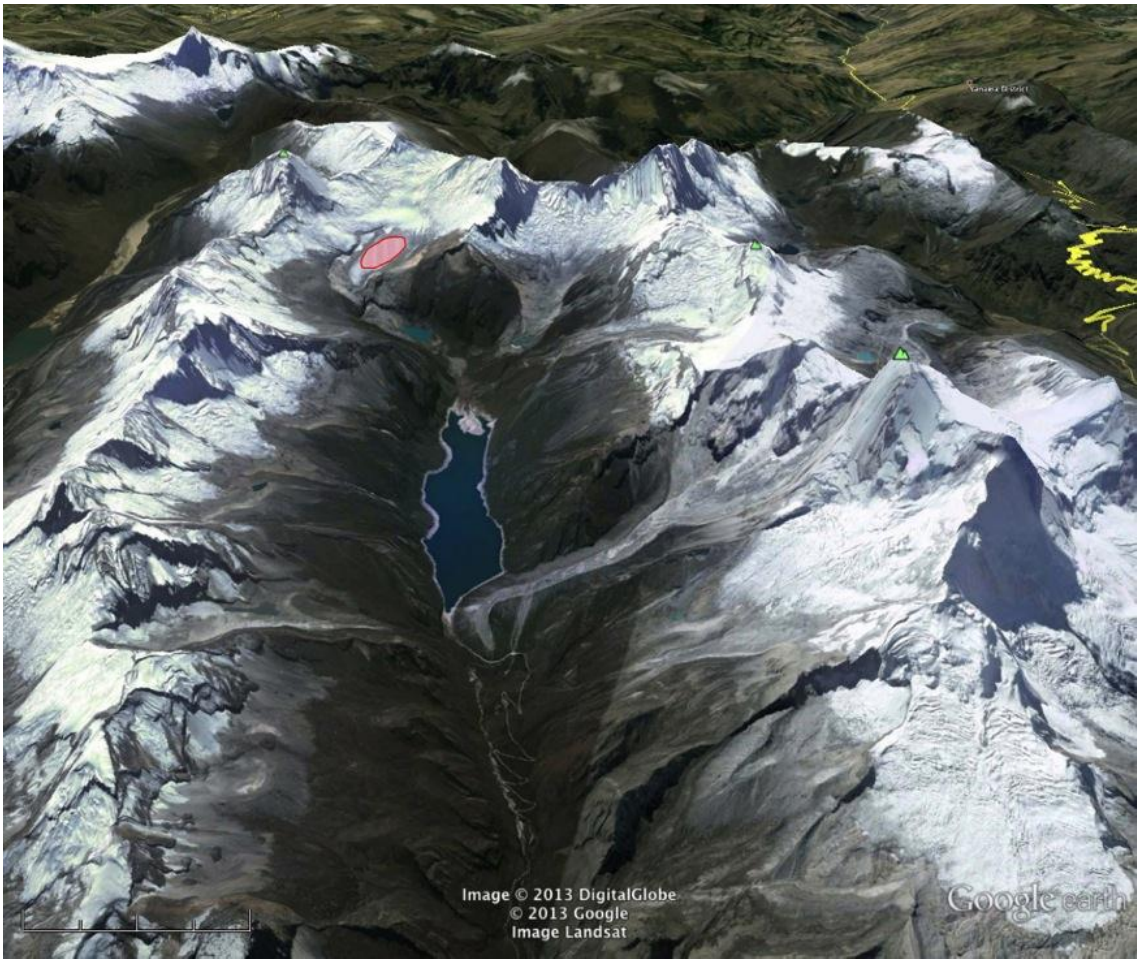
Palcacocha Lake Characteristics	
Total volume at the 4,562 m level:	17,325,206 m^3
Drained volume (-15m):	6,580,182 m^3
Dead volume at 4,547 m:	10,745,024 m^3
Length of open pit canal:	676 m

Left: Palcacocha Lake in 2013 taken from the top of the moraine. The two safety dams can be seen. The dam on the right contains the drainage pipes. Photo: César Portocarrero. Right: Palcacocha Lake in 2008 showing its enclosing moraine; the 1941 breach is visible in the lower right. Photo: Colette Simonds

Conclusions: More than 70 years after Palcacocha Lake killed thousands of people, the lake remains a serious threat to the city of Huaraz. Early works that reduced and reinforced the lake appeared to be effective over the years. When a modestly sized ice avalanche struck the lake in 2003, it launched a wave that the safety works successfully contained. Today, new dynamics are at play in Palcacocha, including a greatly increased lake volume. This exacerbates risk from ice avalanches that can generate larger waves than in a smaller lake, and more water could be released if the moraine were ruptured. This demonstrates why glacial lakes need continued, careful monitoring. Safety measures should be rapidly updated according to emerging needs.

5.2. PARÓN LAKE

Location: 4,174 meters, on the western slope of the Cordillera Blanca. Parón Lake sits at the head of the Parón-Llullán rivers watershed, one of the principal basins draining into the Santa River.



Lake Parón is surrounded by high peaks, including Huandoy (6,395 m) on the south (right). The red circle is the location of an emerging glacial lake. Below that is Artesoncocha, which GLOF-ed twice in 1951.

Risk: High lake volume, proximity of glacial ice, upstream glacial lakes, and steep gradient of side slopes that could avalanche.

History of work: With its complex social as well as physical dynamics, Parón Lake is the most emblematic case of the challenges of glacial lake management in Peru.

At overflow level, the lake's volume is 79 million m^3, making it the largest lake in the Río Santa watershed. It is 3,600 meters long and 750 meters wide, with an average depth of 69.5 meters.

Parón Lake has received attention over the years not just because of its size, but also because its location and volume make it ideal for use as a multi-purpose reservoir for the benefit of agriculture, aquaculture, hydroelectric power, and potable water systems.

Geomorphological evidence suggests that the lake has a long history of instability. For example, the subfloor of the downstream city of Caraz is made up of alluvial materials, mostly boulders and transported material of unknown chronological origin. These were presumably deposited by GLOFs. For generations Caraz residents have asked their governments to provide flood security to their city (Carey, 2010).

1951 photos of surveyors and a sand bag dam built as a temporary barrier below Lake Parón. Photos: Glaciology Unit Office Archives

Additionally, there has been more than half a century of scientific research focused on Lake Parón. The following examples are described in *In the Shadow of Melting Glaciers* (Carey, 2010):

- In 1950, Dr. Ali Szpessy Schaurek measured the displacement velocity of the Hatunraju Glacier, registered as Glacier 506A. These measurements continued throughout the following decade and are still used as reference data.
- In 1951, following two outburst floods from Artesoncocha Lake (located above Parón), Luis Ghilino Antúnez made detailed observations on Parón Lake, noting that new criteria were needed for identifying dangerous glacial lakes. He reported that Parón Lake was dangerous.
- Also in 1951, Dr. Hans Span determined that the reason the GLOFs from Artesoncocha Lake did not have any major effects on Parón Lake was due to low water levels at the time. The low levels allowed the lake to absorb the discharge from Artesoncocha without consequence.
- In 1952, after reviewing the histories of several glacial lakes in the Cordillera Blanca, Dr. Parker Trask concluded that reducing the volume and level of Parón Lake was necessary.
- That same year, the Peruvian engineer Dr. Torres Vargas recommended reconnaissance surveys of the lake's natural drainage channel and dam. These became the first surveys carried out in the Parón area.
- In 1964, Jorge Matellini—also a Peruvian engineer—recommended focusing on Parón Lake as the highest priority lake to manage in the Cordillera Blanca, mostly because of its size.

Left: The path taken by the 1951 outburst floods from Artesoncocha into Lake Parón. Google Earth imagery is from 2012. Right: Lake Parón showing the moraine descending from Huandoy that blocked the valley and created the lake. Photo: César Portocarrero

Some safety measures were implemented after the 1951 outburst floods from Lake Artesoncocha including placing sand bags over the natural dam. Topographical studies examined lake characteristics for future drainage projects.

In 1966, the Peruvian Santa Corporation (the entity that led development in the Ancash Department through 1967) contracted the services of several internationally recognized experts to analyze glaciers and glacial lakes in the Cordillera Blanca. They included Dr. Louis Lliboutry (glaciology), André Pautre (geology), and Georges Post (soil mechanics). These scientists reached several important conclusions regarding the potential triggers that could lead to GLOFs from Lake Parón, including:

- Seismic activity could affect the Hatunraju moraine and alluvial fan along the right side of the lake through a process of liquefaction.
- A karst network runs below the ice of the Hatunraju Glacier, contributing to ice melt. The hollows left by the melting ice could fill with water and break loose violently.
- An excessively rapid discharge from the lake could erode the moraine.
- The moraine could become damaged by blocked infiltration networks, ice calving from the glacier, or outburst floods from smaller glacial lakes above.

With so many potential triggers for a GLOF from Lake Parón, the scientists hired by the Peruvian Corporation of Santa concluded that "taking into account the unknown and dreadful consequences that a rupture of the Lake Parón dam would have, the most sensible course of action is to drain the lake as much as possible." (Corporación Peruana del Santa, 1967).

They presented three possible solutions:

- Cutting a V-shaped groove into the moraine. This alternative was rejected because it would destabilize both slopes (the lateral moraine on the left side of the lake and the alluvial cone on the right side).
- Pumping water out of the lake. This would be a temporary and expensive solution.
- Boring a tunnel along the rocky right side of the lake and digging through the bottom of the lake in the thinnest stratum of detritus. This was chosen as the safest option.

Dr. Lliboutry recommended completely drying out the lake in order to study the stability of its lateral slopes. However, later studies by the Glaciology Office and private consulting companies showed that alternative methods could ensure safety while still allowing the productive use of water from the lake. The possibility of regulating the lake as a reservoir for the summer months was also being explored (Coyne et Bellier, 1966).

A technical advisor of Siderperu (the state-owned steel maker) encouraged his company's president and general manager to provide funds for the water regulation works at Parón Lake. The steel-making company would benefit from electricity produced by hydropower from Lake Parón. This led Electroperú (Peru's top public sector energy company) to provide additional funds for the next stage.

Tunnel excavation commenced in 1969. After advancing 1,063 meters, construction stopped in 1972 because of a dispute between the project's supervisors and its contractors. The project was then abandoned, unfinished, for ten years.

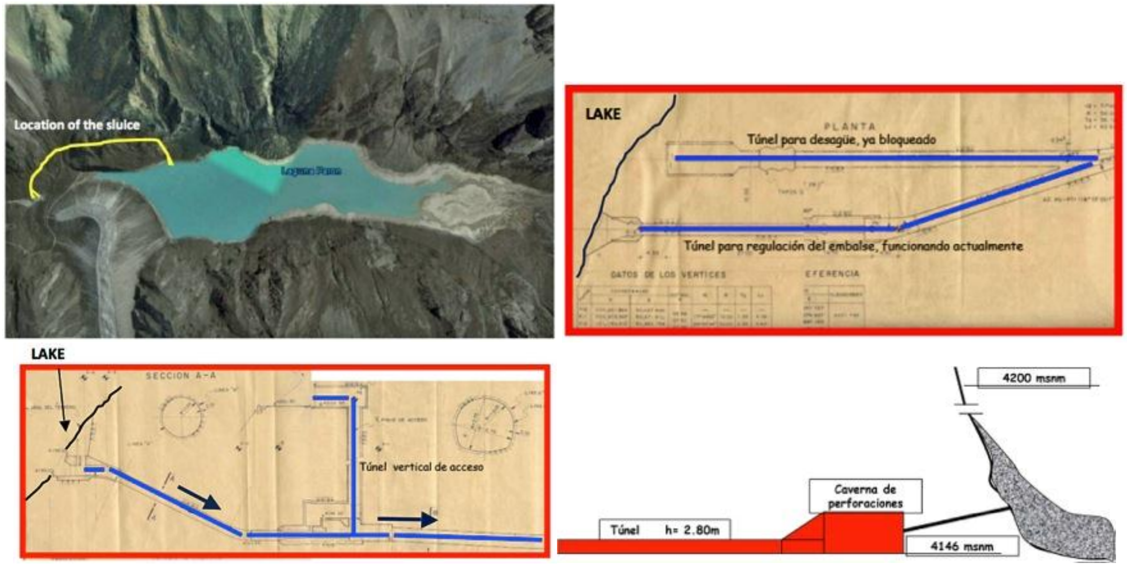
Construction recommenced in August 1982 under the guidance of Electroperú and the National Water Authority's Glaciology Unit. The final length of the tunnel reached 1,245 meters. Drainage of the lake began in February 1982 through two holes with a diameter of 60 centimeters each.

While drillers celebrated the success of the first hole, engineers who measured the lake's outflow found that it was only half of what was projected. Despite a 54-meter head and a 60-centimeter diameter hole, only about half of the calculated 4 m^3/second was being delivered. It turned out that the level of the tunnel, and hence of the entrance holes, was too low—it was practically adjacent to the sediments at the bottom of the lake. The holes had been drilled at 4,146 meters of altitude, while the recommendations from engineering company Coyne et Bellier called for the holes to be drilled 9 meters higher—at 4,155 meters.

The two holes had opened into the bottom of a debris cone that was clogging the tunnel. To unclog it, the drillers inserted a blade into the hole to "beat" the material and allow it to flow out. When water rushed out much faster than expected, two drillers were almost killed.

The work's supervisor was blamed for allowing material from the digs to be thrown at the foot of the talus, thus obstructing the orifices. Later, when the final tunnel connection was completed, the designer was careful to ensure that the mouth was at the 4,155-meter level as recommended by Coyne et Bellier.

Drainage began midway through 1983 and continued into 1984, but was interrupted by a landslide into the spillway at the junction between loose material at the entrance to the canal and the rocky massif. Repairs took several months in 1984, delaying completion of the drainage process until 1985.



Diagrams of the sluice and tunnels of Lake Parón. The Google Earth view is from 2012. The diagrams were drawn for construction in the 1980s. Source: César Portocarrero

The Dam Characteristics Report was prepared at the completion of the drainage process to establish parameters for regulating the lake and included the following conclusions and recommendations (Consultores Asociados, 1986):

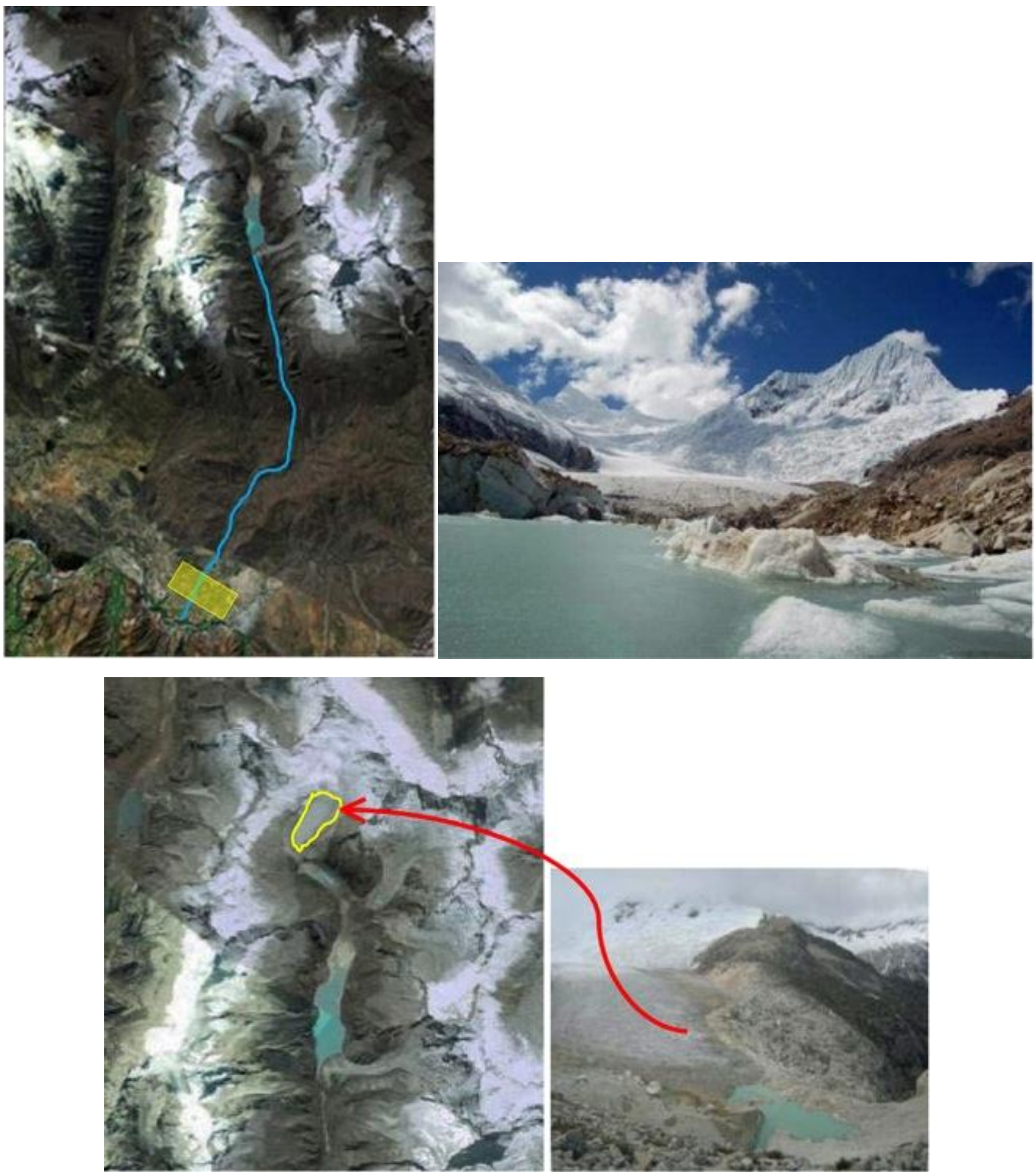
- No fossil ice is present under the surface of the lake that could produce a karstic phenomenon.
- The materials forming the natural dam are fairly uniform and covered by thick, impermeable clay and other fine sediments.
- Slopes of the dam upstream and downstream ensure high stability even during strong seismic events.
- The drainage rate for the lake should not exceed 20 centimeters of lake level per day to prevent causing landslides into the lake.
- A water level of 4,190 meters above sea level should be set as the maximum level of the lake as a reservoir, with 4,185 meters being the safest level (at 4,185 meters the freeboard is 15 meters). For protection against surges and seismic events, the lake level should remain 15 meters below the top of the natural dam. A 10-meter height difference (water levels at 4,190 meters) would necessitate updating risk assessments and raising the level of the natural dam.
- Strong earthquakes can generate considerable wave surges because of the regular shape of the basin, the steep surrounding slopes, and the funnel shape of the lake.
- The near-vertical cliffs on either side of the lake have not been studied and little is known about their characteristics.
- The water supply into the lake is sufficient for a combination of agriculture, potable water supplies, electric power generation, and other activities downstream.

The final stage of the project was completed in 1992.

The following account illustrates how social dynamics can affect what might appear to be a purely engineering project, such as simply reducing the risk of a glacial lake while generating electric power from its waters.

Upon completing all construction in 1992, Electroperú transferred control of the facilities to Cañón del Pato hydropower plant. In 1995, Cañón del Pato Central Hydroelectric was privatized and sold to Duke Energy, which assumed control of Parón and Cullicocha lakes. Over the following decade, downstream water users felt that Duke Energy was managing the water supply purely for electrical generation without consideration of the water needs of local communities. In 2008, after years of complaints, community members blockaded the dam's lake control facilities and prevented access by Duke Energy's personnel.

In 2013, five years after the community seized the facilities, no solution has been found. No one maintains the lake's controls. The flood regulation system started failing in 2011. A system failure could cause the floodgates to open completely out of control, leading to significant damage in the river channel.

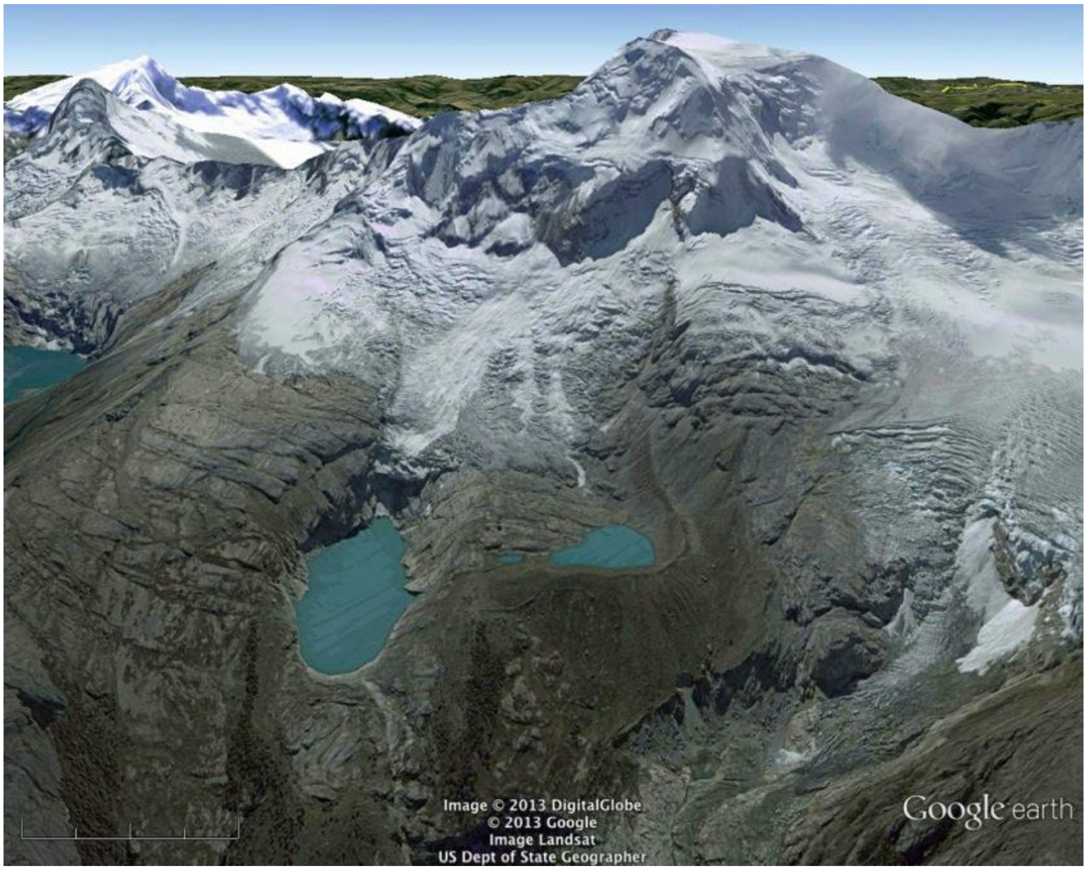


Top left: Potential trajectory of a GLOF from Lake Parón down to the city of Caraz. Upper right and below: An emerging lake in 2010 being formed by retreating glaciers upstream from Artesoncocha and Parón lakes. Photos: Jesús Gómez

Conclusions: Parón Lake illustrates complexities of glacial lake management that go beyond engineering. Engineering challenges included drilling drainage tunnels at precise altitudes and building a hydropower generation facility. Social challenges include managing the lake for multiple uses and satisfying the local community that their needs are being addressed. Parón Lake demonstrates that if the local people feel neglected, an entire management effort can be undermined. To be effective, lake management needs to be part of an integrated watershed management process with participation from all stakeholders.

5.3. LAKE 513

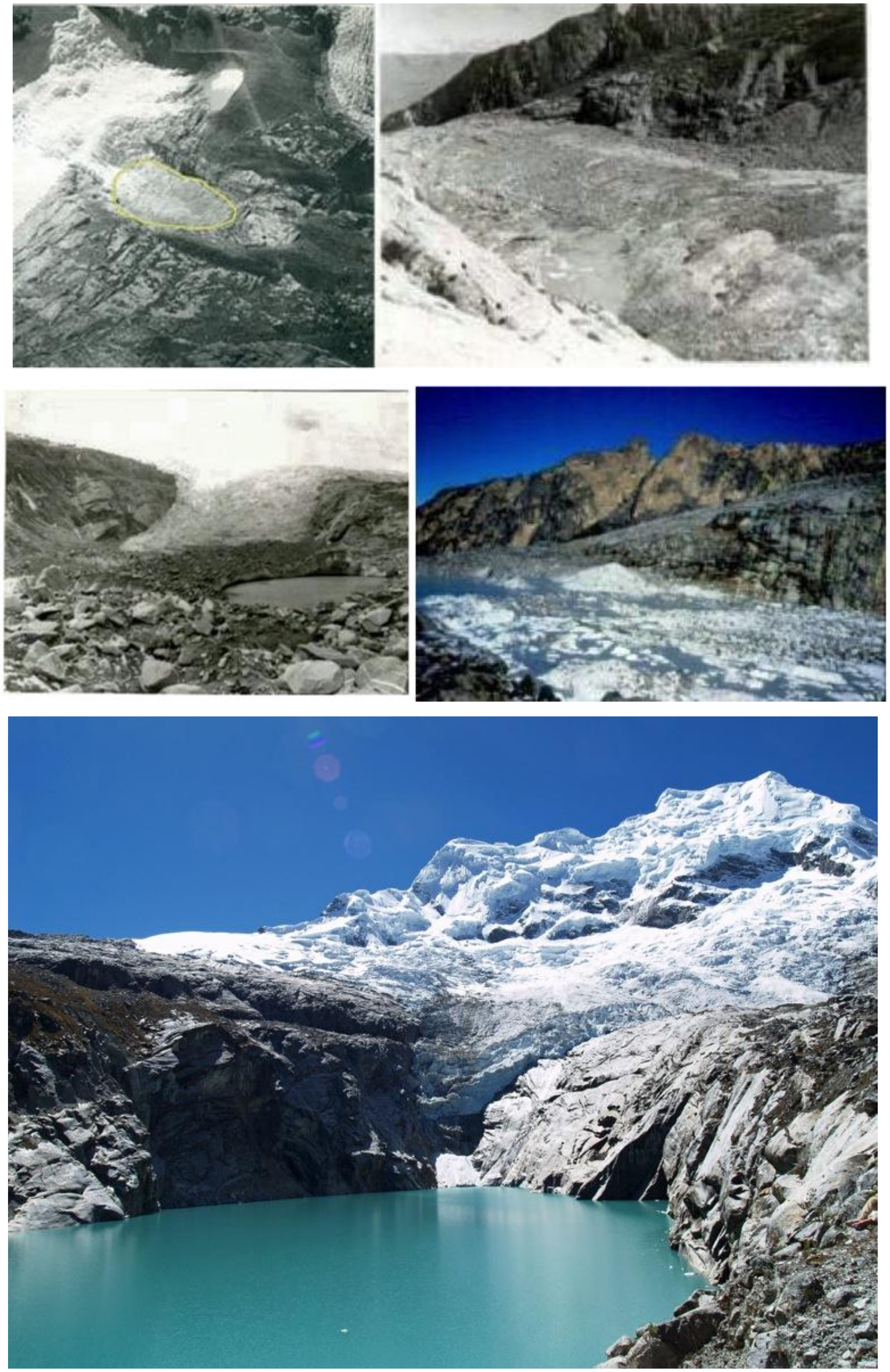
Location: 4,431 meter, Lake 513 is named because the lake emerged from Glacier 513 in the National Glacier Inventory (Ames, et al., 1988). It is on the west side of the central Cordillera Blanca below Hualcán Peak.



Lake 513 is the largest lake below Hualcán Peak (6,122 m). The retreating glacial tongue is still poised directly above the lake, but the largest flood event resulted from an ice avalanche that originated near the summit of the peak in 2010.

Risk: The lake experienced several small outburst floods in the 1980s and a larger one in 2010 resulting from ice falling from hanging glaciers. Communities in the valley below suffered from damage to households, the riverbed, the access road, agricultural fields, and to the La Merced thermal baths in Hualcán. There is still considerable risk of ice avalanches striking the lake.

History of work: The glacial lake started forming in the early 1970s (before then the basin was filled with glacial ice). At that time, engineers from the Basic Studies and the Glaciology Studies divisions of the Glaciology Unit started visiting the site regularly to determine if actions might be needed. The lake finished forming in the late 1980s and immediately experienced several small GLOFs resulting from falling ice from hanging glaciers.



Chronology of an emerging glacial lake. Top left: Aerial photo of Lake 513 as a puddle on the surface of the glacier in 1962; the yellow circle marks the approximate size of the emerging lake. Top right and middle left: Emerging ponds in the early 1970s; these ponds would merge into Lake 513. Middle right: Lake 513 almost completely formed in the late 1980s. Bottom:

Lake 513 showing the hanging receding glacial tongue and Hualcán in 2010. Black and white photos: Glaciology Office Archives, Color photos: César Portocarrero

The remoteness of the area and the lack of resources available for a major project led the Glaciology Unit to install temporary siphons in 1989 (with financial support from the British and Austrian governments). These plastic pipes, 10 inches (254 millimeters) and 12 inches (305 millimeters) in diameter, were used to lower the water level by about 6 meters. In 1992, drilling started for a tunnel that would lower the water level by 20 meters. The work was financed by the Peru's Civil Defense Institute.

The initial siphoning process to lower the water level of Lake 513 in the late 1980s. Siphoning was an interim measure until funding was received for construction of the tunnel. Photos: César Portocarrero

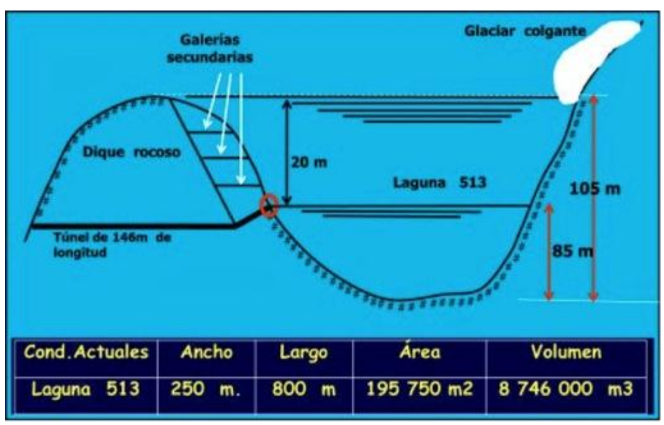


Figure 5-1 Diagram of the Tunnel Draining Lake 513. Diagram: César Portocarrero

The original plan was for the tunnel to contact the lake at a depth of 20 meters, using underwater blasting and placing devices inside the tunnel to regulate the outflow. However, this plan was abandoned during construction when the driller became afraid to blast the connection to the lake at such a depth. Instead, a sloping shaft was built from which connections would be added at increasing depths of 5, 10, 15, and 20 meters.

Twenty meters of freeboard was left to the basin's natural rock rim in order to contain potential wave surges created by ice avalanches falling into the lake.

Red dots mark the tunnel entrances on Lake 513. The photo on the right shows the lowest entrance. Photos: César Portocarrero

During the ensuing 18 years, the combined drainage tunnel and freeboard fulfilled the mission to regulate the flow produced by moderate avalanches from Mt. Hualcán. Then, on 11 April 2010, a very large avalanche, presumably in the 300,000 to 400,000 m^3 range, caused a hydrodynamic surge and a wave higher than 20 meters that overflowed the works and flooded the Chucchun River for approximately 30 hours, destroying bridges, farmland, and houses.

The source and path of the 2010 ice avalanche from Hualcán that fell into Lake 513. There is potential for many more such avalanches. Photos: César Portocarerro

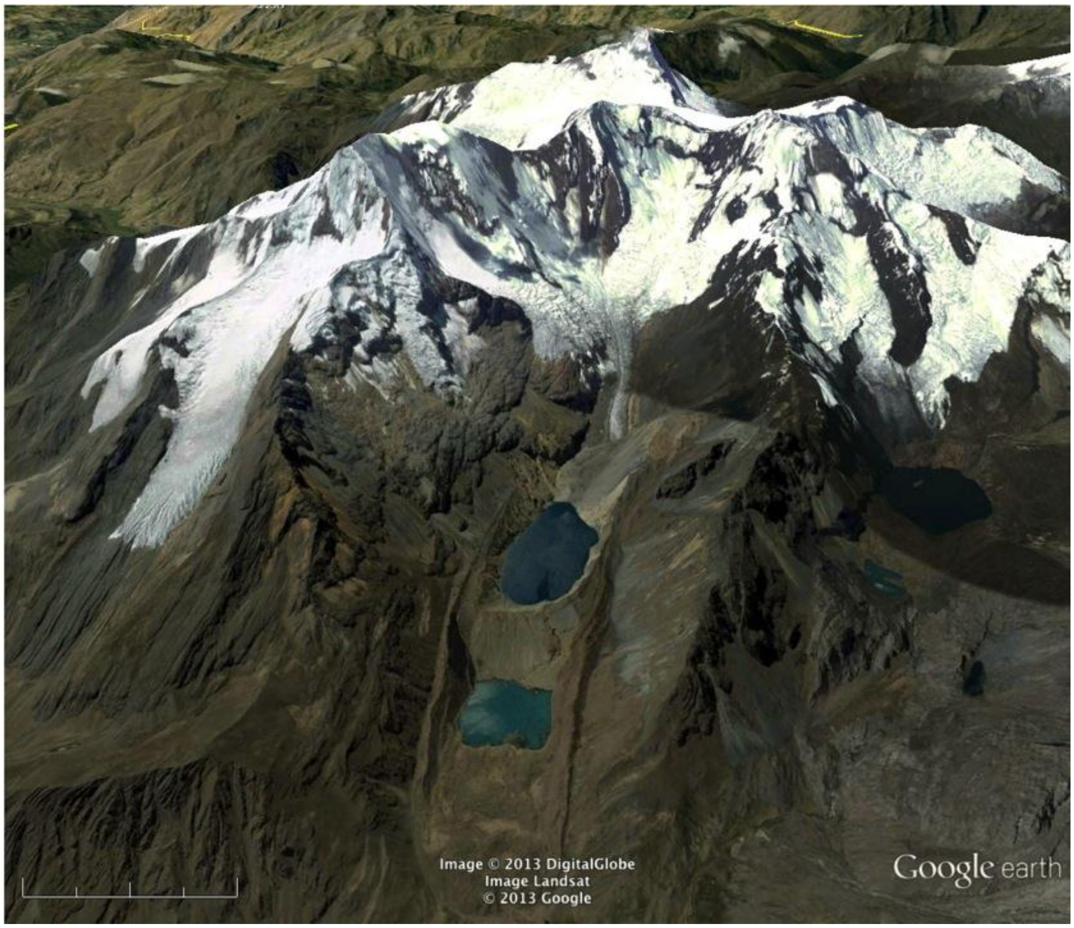
International experts were called in to examine the lake (Prof. Wilfried Haeberli from the Institute of Geography at the University of Zurich and Prof. Stephen Evans of Waterloo University in Canada). They confirmed the success of the safety works that had been built into Lake 513, which prevented a much bigger flood that would have damaged the Chucchun River course much more severely.

However, evidence suggests that there is a continued risk of a GLOF. An early warning system was installed in the Chucchun River watershed as a complement to the work carried out on Lake 513 in the 1990s. There is also a proposal under consideration to drill a second tunnel that would further reduce the risk and store some water for the needs of Chucchun River basin users.

Conclusions: This example reveals that the increasing frequency of glacier avalanches in many locations requires reviewing design concepts and principles from previous projects to be certain they can control current risks.

5.4. SAFUNA ALTA LAKE

Location: 4,360 meters, in the Quitaracza River basin, Pomabamba province of Ancash, northern Cordillera Blanca.



Safuna Alta and Baja lakes (middle of image) below Pucahirca Peak (6047 m).

Risk: The moraine dam appeared to be highly unstable. The risk was compounded by dangerous conditions on surrounding glaciers.

History of work: In the early 1960s the Glaciology Unit recommended building a 47-meter-long drainage tunnel that would prevent the lake's water level from rising above 4,360 meters. In April 1970, a tunnel was completed that was supposed to reduce the water level by 38 meters (Ames and Francou, 1995). However, by then the water level had dropped by 30 meters, so that the tunnel was above the lake's new water level. A month later, a large earthquake severely damaged the tunnel. A new 159-meter-long tunnel was built that, like the previous tunnel, had to be excavated through morainic material. (Report of the Glaciology and Lake Control Office of the Corporation Peruana del Santa, 1972).

However, the lake's water level continued to drop so that in 1974 the level was 10-plus meters lower than the level of the second tunnel and continued to decline in subsequent years. The lake's depth was 154 meters in 1967, 98 meters in 1973, 119 meters in 2001, 81.5 meters in 2002, and 84 meters in 2010.

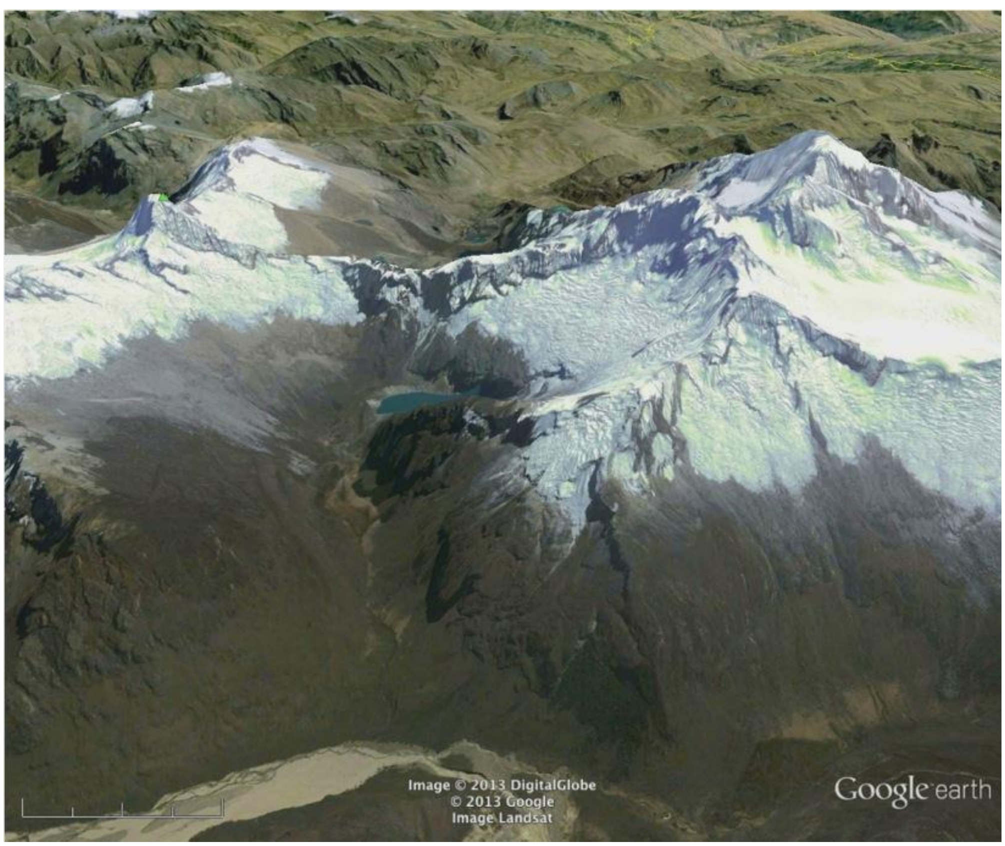
In 2002, a rockslide created a wave of at least 80 meters in height (Reynolds, 2003). The wave damaged both tunnels, but did not destroy the moraine.

Safuna Alta Lake. Left: Locations of the two tunnels drilled into the moraine in the early 1970s as the lake's level dropped on its own. Right: The source of the landslide in 2002 that launched a wave at least 80 meters in height. Photos: César Portocarrero (1974)

Conclusions: Highly variable water levels generally result from a permeable moraine. Such moraines are usually weak in structure. It is vital to keep water levels low in glacial lakes with weak moraines. In this case the tunnels may have been moderately helpful in rapidly draining the lake during a large-wave event, but were damaged in the process.

5.5. JANCARURISH LAKE

Location: 4,500 meters, on the west flank of Alpamayo Peak, northern Cordillera Blanca.



Jancarurish Lake with the famous Alpamayo (5,947 meters) on the left (northeast) and Quitaraju (6,036 meters) on the right (east).

Risk: Threatened by hanging glaciers and contained by a loose and poorly consolidated moraine.

History of work: To drain Jancarurish Lake, the Lakes Control Commission cut an open V-shape through the moraine in 1951. Sandbags were used to stem the flow of water and allow digging on dry ground. Depending on the amount of water flowing into the lake, the water level rose from 20 to 50 centimeters per day. At the end of each day the dam of sand bags was opened to allow the water to flow, carrying with it fine materials that had settled.

For unknown reasons, the head of the work team at Jancarurish Lake decided to leave the sand bags in place for four consecutive days. The height of the dammed water might have exceeded a meter by the time the sandbags were removed. The ensuing large flow of water eroded the moraine and emptied the lake in a GLOF.

This GLOF seriously damaged the small Jancarurish hydroelectric plant in Los Cedros, which had been built during the 1951 construction of the Cañón del Pato hydroelectric power plant. It also damaged farmland, roads, and other public and private infrastructure in that area. Property was destroyed as far as the port of Chimbote, more than 150 kilometers downstream.

Left: Alpamayo Peak (5947 m), perhaps the most iconic peak of the Cordillera Blanca; Jancarurish Lake sits below the visible glacial tongue. Right: The V-shape cut into Jancarurish Lake's moraine in 1951. Photos: César Portocarrero (1990)

Conclusions: Open pit cuts through moraines are risky because the cut is especially vulnerable to erosion before pipes and reinforcements are added. Early engineering works in the Cordillera Blanca did not have the benefit of today's knowledge, including the use of important safety measures, such as early warning systems. Today, temporary early warning systems should be installed as a precaution against possible unforeseen events, including ice avalanches.

5.6. HUALLCACOCHA LAKE

Location: 4,355 meters, on the eastern flank of Chequiaraju Peak, at the head of the Paccha glacial valley, which drains into the Ulta valley.

Huallcacocha Lake with its safety dam visible lower right.

Risk: After the earthquake of May 31, 1970, old geological, glaciological, and topographic studies were updated throughout the Cordillera Blanca. They indicated that, because of the volume of stored water in Huallcacocha Lake, damage to the lake's inner slope and settlement within the 1960s-era safety structure necessitated additional security works. The risk was greatly magnified by hanging glaciers above. The Studies Division of the Glaciology Unit recommended extensive new safety works.

History of work: This lake was treated twice. In the 1960s the former Control Bureau of Cordillera Blanca Lakes lowered its water level by 10 meters, and then built a sluice of stone masonry one square meter in cross section and 102 meters long. A 10-meter-high artificial dam, stabilized by riprap, was built on top of the structure.

Safety works on Huallcacocha Lake: 1950s construction (top) and the finished result in the 1960s. Photos: Glaciology Office Archives

New tunnel being constructed in the early 1980s. First the channel was cut, then the tunnel built, and finally the canal was covered with a safety dam. Photos: César Portocarrero

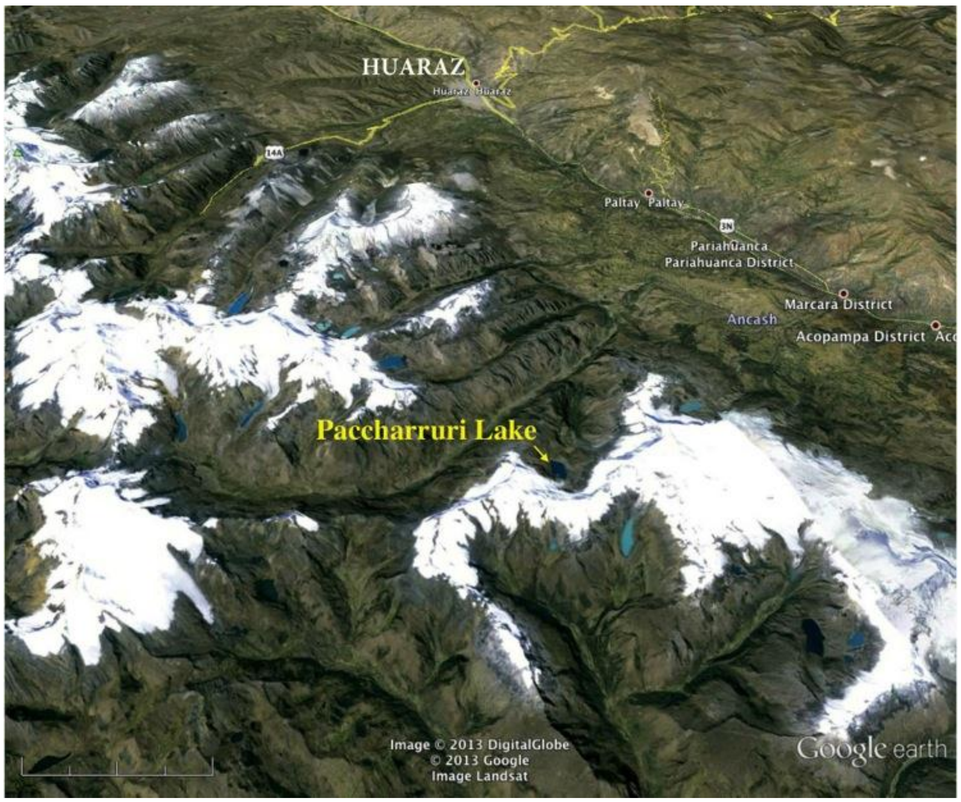
Huallcacocha's completed safety dam from below (1978) and above (2013). Photo: César Portocarrero

New work following the 1970 earthquake required completely removing the original 20-year-old construction. The lake was then lowered by 14 meters through an open pit at the front of the moraine. The next phase involved building a reinforced concrete pipe 1.8 meters in diameter and 77 meters in length. Inflow and outflow canals were built of stone masonry. To prevent soil erosion by water exiting the conduit at high velocity, a fast exit waterway of reinforced concrete and an energy sink were added. Finally, to contain potential surge waves resulting from ice masses falling into the lake, a 20-meter-high earth dam with an impervious waterproof core was added. The outside walls were finished with stone masonry sealed with cement mortar. During construction a mass of ice fell into the lake, but did not damage the work that was underway.

Conclusions: Because the original work from the 1960s was not sufficient to withstand a large earthquake, it had to be removed and rebuilt 20 years later.

5.7. PACCHARRURI LAKE

Location: 4,445 meters, below Nevado Paccharaju, east of the town of Marcará.



Paccharruri Lake is one of a string of glacial lakes near the town of Marcará. (This is a distant view because the satellite image quality is low in that region.)

Risk: A glacial tongue was in contact with the lake. If it broke it could cause a wave.

History of work: To control this lake, the former Control Bureau of Cordillera Blanca Lakes built a stone masonry-covered duct and an 8-meter-high earth dam in 1964–1965.

The 1970 earthquake changed the morphology of the glacier tongue that was still in contact with the lake, leaving only a short freeboard of the earth dam. Engineers in the Glaciology Unit determined that this freeboard would not have been sufficient to withstand a large wave. (Note: At the time, there were few published studies to refer to. Thus, decisions regarding glacial lake management were made during discussions among Glaciology Unit civil engineers, geologists, and hydrologists.)

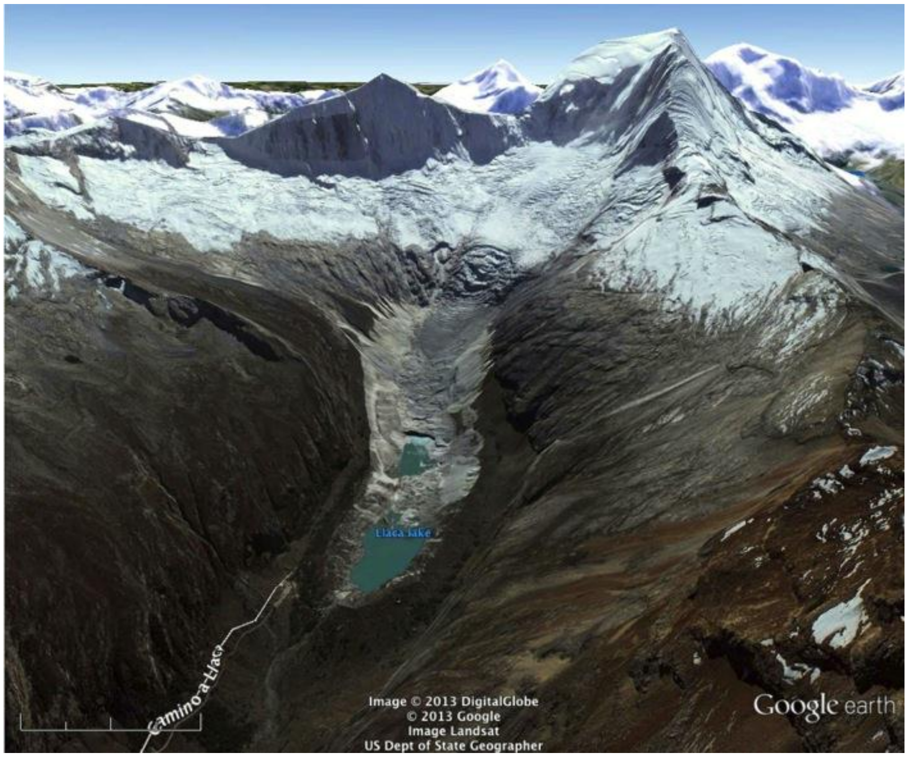
Paccharruri Lake showing the sluice cut to lower the water level (left) and the completed safety dam and outflow canal beyond the covered sluice. Photos: César Portocarrero

Work began in the early 1980s to lower the level of the water surface by 10 meters. A covered sluice 71 meters long and 1.8 meters in diameter was built, over which an 18-meter-high safety dam was added. As in other works of the same type, covered access and exit conduits were built to prevent erosion of the moraine material and safely move water downstream.

Conclusions: Monitoring the lake revealed the need for new works, which shows the necessity of continued monitoring of already treated lakes (a principle that applies to all cases). The structure of the morainal material plays a large role in its ability to withstand seismic and other events. For example, moraines that are primarily composed of clay are much more resistant to erosion and shear stresses.

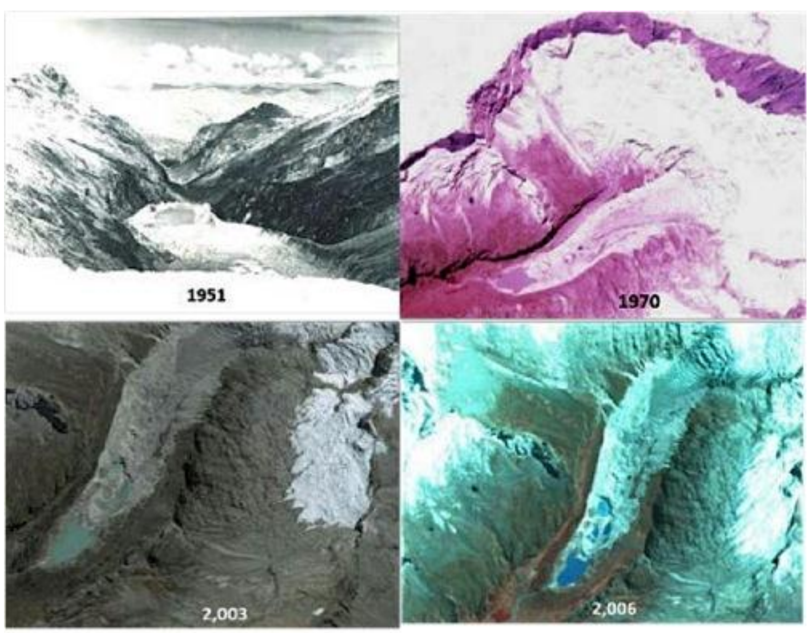
5.8. LLACA LAKE

Location: 4,409 meters, at the head of the creek of the same name, northeast of the city of Huaraz.



Llaca Lake showing the rapidly retreating Ranrapalca Glacier below Ranrapalca Peak (6,162 meters).

Risk: After the 1970 earthquake, the 1960s-era works at Llaca Lake settled and the vent pipe was damaged, raising an urgent need to reassess the safety of the lake and to build further protection works.



The evolution of Llaca Lake: Top row, left: 1951; right: 1970. Bottom row, left: 2003; right: 2006.

History of work: First, steps were taken to improve access roads and camp sites. Once these improvements were finished, engineers lowered the lake by 10 meters through an open pit cut. After the lake was lowered, a 48-inch(1,219 millimeter)-diameter steel pipe was installed. When completed in 1974, the lake's maximum depth was 19 meters.

Left: Looking upstream from the safety dam at Llaca Lake. Right: The view downstream across Llaca Lake. Photos: John Harlin

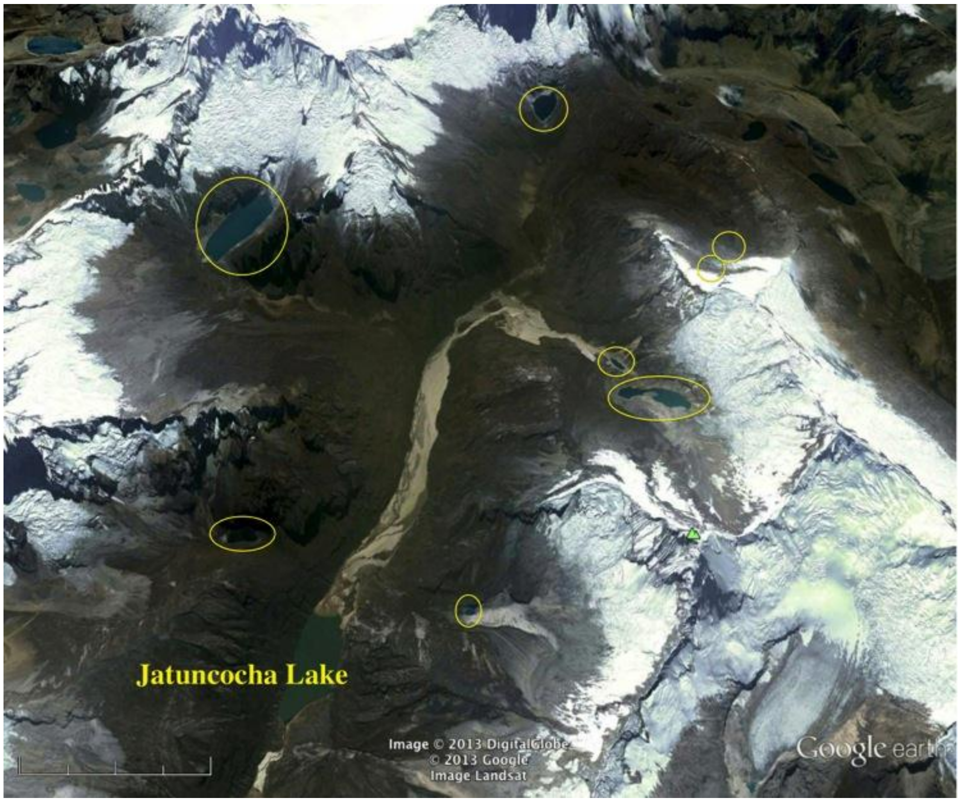
Llaca Lake's safety dam and sluice in 2013. Photos: John Harlin

From 1976 to 1977, the second stage of the project involved building a 10-meter-high earth dam inside the open pit cut (on top of the steel pipes), with an impermeable core and stone walls finished with cement mortar-sealed joints.

Conclusions: This is one of the larger and better projects using reinforced concrete pipes covered by earth dams. The infrastructure appears to be in perfect working order nearly 40 years after final construction. It is not known whether any potential GLOF-triggering events took place during this time. However, current understanding of the distance that ice avalanches can travel (Alean 1985, Haeberli 2013), combined with a large number of hanging glaciers on the peaks above Llaca Lake, show that the lake is heavily threatened by potential triggers.

5.9. JATUNCOCHA (BIG) LAKE

Location: 3,886 meters, Santa Cruz valley, province of Huaylas, northern Cordillera Blanca.



Jatuncocha Lake is useful as a catchment basin for upstream glacial lakes, circled in yellow.

Risk: Hanging glaciers above and several emerging upstream glacial lakes. Jatuncocha Lake serves as a reservoir to catch and retain debris flows from upstream lakes. Drainage pipes tend to cause downstream erosion (threatening downstream communities) after a GLOF event.

History of work: Safety works for Jatuncocha Lake were built in the early 1960s. A V-cut was made in the moraine, two parallel steel pipes (each 1.2 meters in diameter) were laid in the cut, and a dam of compacted earth was then built over the pipes to contain waves.

Upstream from Jatuncocha is a glacial lake called Low Artizon Lake. In February 2012, Low Artizon Lake overflowed in a GLOF. The safety structures built 50 years earlier for Jatuncocha Lake successfully contained the surge.

Although the Jatuncocha dam contained the flood, the flow through the two pipes reached more than 10 cubic meters per second down the steep valley below, causing substantial erosion and destruction of homes, property, and roads.

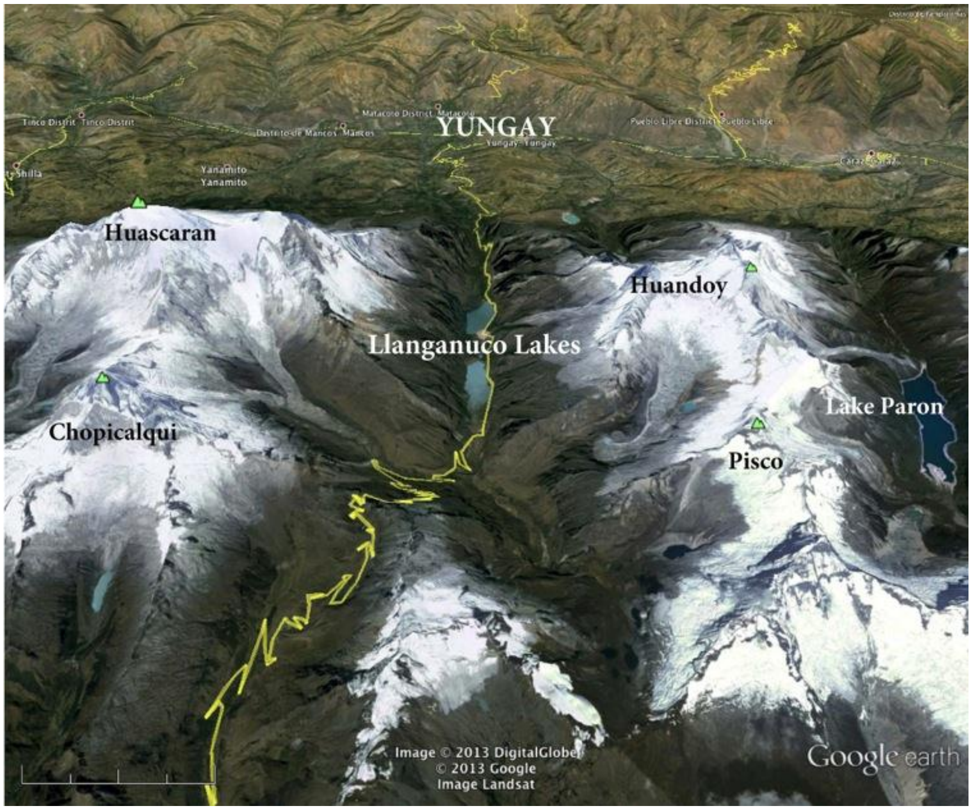
Top left: The path cut through Artizon Lake's moraine during its 2012 GLOF. Top right: Floodwaters resulting from Artizon's GLOF almost filled the drain pipes under Jatuncocha's dam. Bottom left: Debris from the 2012 Artizon GLOF. Bottom right: Relatively normal flows through the Jatuncocha tunnels. Photos: César Portocarrero

Damage in the Santa Cruz valley downstream from Jatuncocha during the 2012 GLOF. Photos: Hidroeléctrica Santa Cruz

Conclusions: The Jatuncocha Lake safety works were built 50 years prior to a GLOF from an upstream lake in 2012; this was the first time that these structures were fully tested.

5.10. LLANGANUCO LAKES

Location: 3,863 meters, Yungay province of Ancash, northern Cordillera Blanca.



The Llanganuco lakes are directly upstream from the city of Yungay.

Risk: Rapid lake growth resulting from recent avalanches that impounded the lake.

History of work: The great 1970 earthquake triggered several ice avalanches from the peaks of Huandoy and Huascarán, which in turn created an impoundment that raised the level of High Llanganuco Lake. The lake's volume grew fivefold and its length grew by more than two kilometers, flooding all the roads in the area.

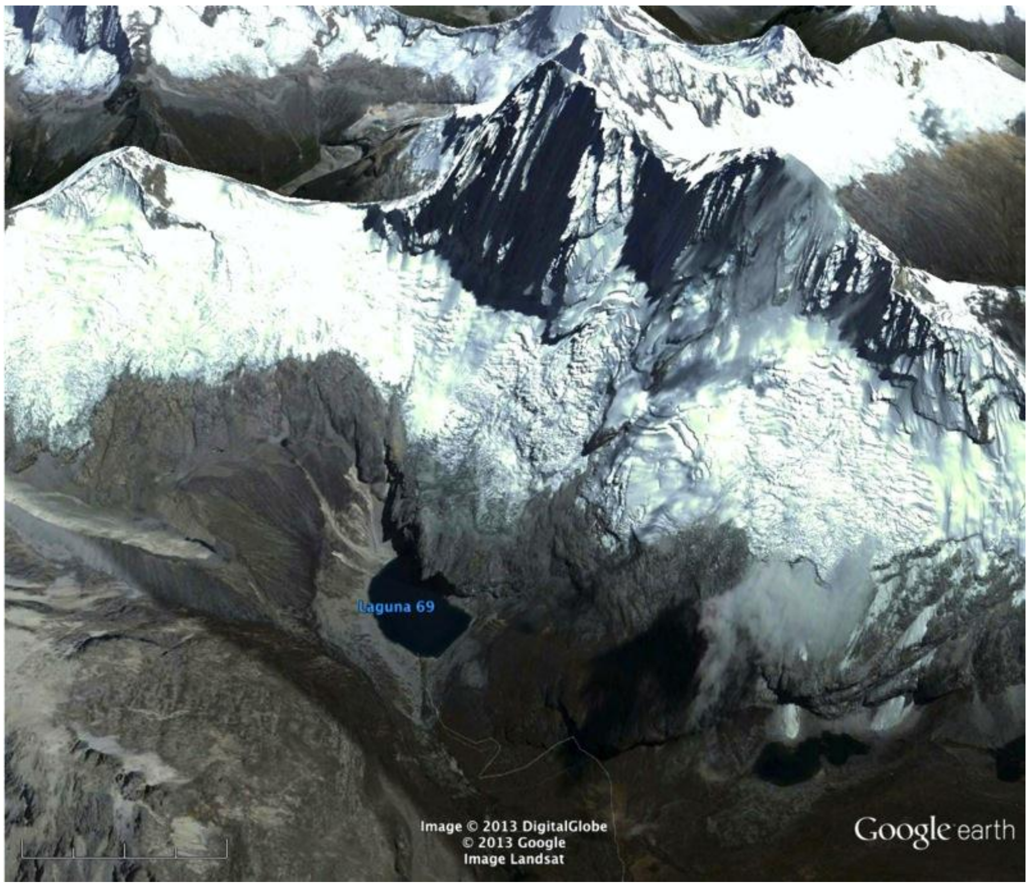
The Llanganuco lakes from upstream, showing Huandoy on the right. Photo: César Portocarrero

Work to drain the lake started immediately after the earthquake to mitigate an outburst of the newly dammed lake. The safety measures were primarily directed at lowering the water level, which also allowed safe passage for road travelers headed toward the east side of the Cordillera Blanca. A 540-meter-long cut was opened in the debris dam, and masonry walls were built to protect the road. The Low Llanganuco Lake's small safety dam was also raised.

Conclusions: No issues have been observed in these lakes after the safety works were installed. Engineers believe this safety record illustrates that rapid preventative action can reduce long-term risk.

5.11. LAKE 69

Location: 4,604 meters, at the head of the Llanganuco valley, at the base of ice-covered Mount Chacraraju, on the western slope of the Cordillera Blanca, east of the town of Yungay.



Lake 69 is in the direct fall line from glaciers on Chacraraju Peak (6,112 meters).

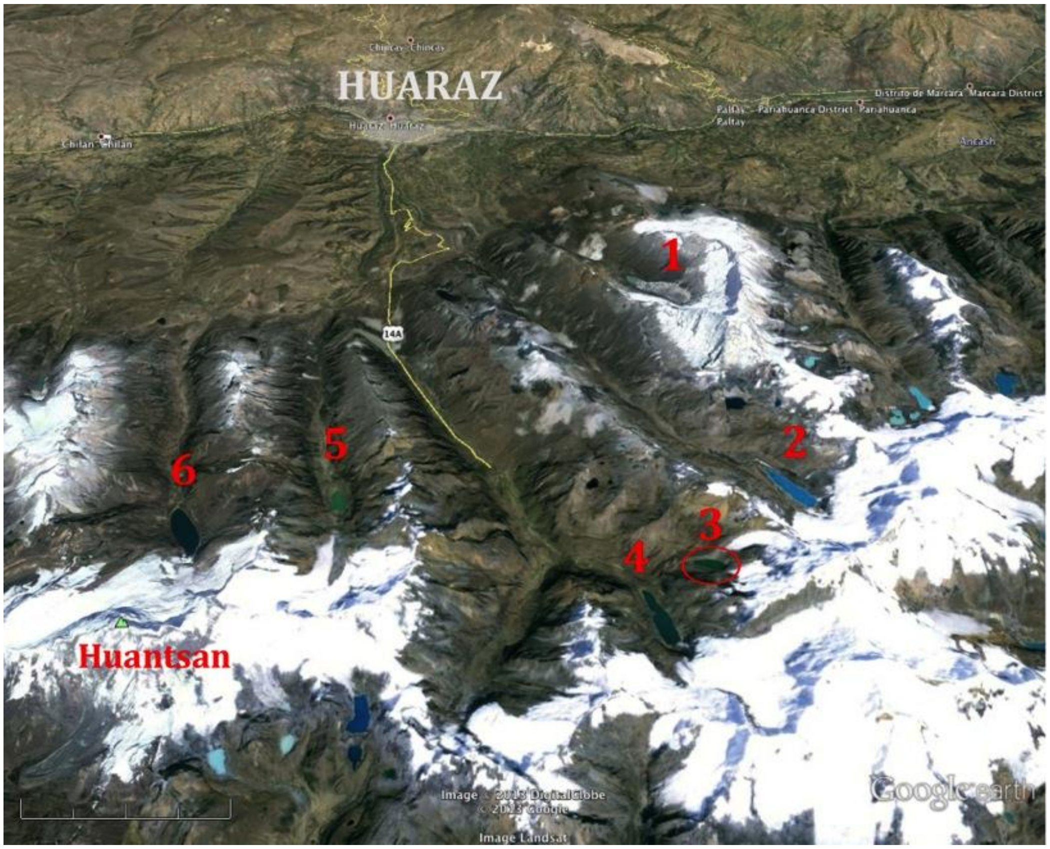
Risk: Threatened by one of Chacraraju's heavily fractured hanging glaciers, which frequently drops ice into the lake. If a large piece of ice fell into the lake, the resulting GLOF would pose a serious threat to downstream communities.

History of work: Originally 60 meters deep, with 3.1 million cubic meters of stored water, the lake was treated in 1989 by lowering its surface level 10 meters, from 4,620 MASL to 4,610 MASL. This drained 965,000 cubic meters of water—nearly a third of its volume. The water was removed by deepening the natural drainage channel along a 190-meter length. The new channel was then reinforced with stones for 150 meters of its length, at a width of 5.8 meters.

Conclusions: Huascarán National Park guards are stationed downstream of Lake 69. They report that despite ice frequently falling into the lake, there have been no GLOFs or problems from this lake.

5.12. CUCHILLACOCHA LAKE

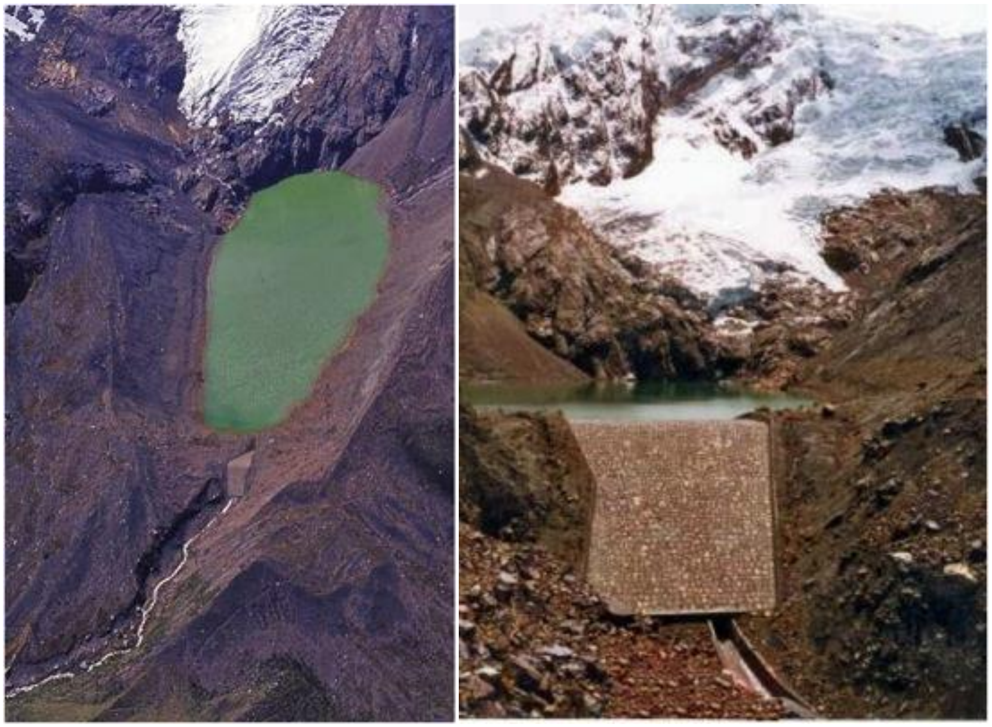
Location: 4,620 meters, at the foot of Nevado Pucaranra, east of Huaraz. Also known as Bayococha.



Some of the glacial lakes immediately east of the city of Huaraz. (1) Llaca Lake, (2) Palcacocha Lake, (3) Cuchillacocha Lake, (4) Tullparraju Lake, (5) Shallap Lake, (6) Rajucolta Lake.

Risk: When it was re-surveyed in 1971 following the 1970 earthquake, the lake was visibly threatened by a 50-meter-thick tongue of a nearby hanging glacier. If the glacial tongue broke off, falling ice would create a large avalanche that would hit the lake.

History of work: Probably due to its location above Huaraz, Cuchillacocha became one of the first lakes to be treated in Peru. In 1942, local authorities excavated a notch into the terminal moraine to lower the water level by 14 meters, leaving an open canal. Fourteen years later, in 1956, the Cordillera Blanca Lakes Control Commission installed a 42-inch-diameter pipe, over which they built a 4-meter rammed earth dam. In 1971, after the 1970 earthquake that devastated this region, the Santa River Corporation decided to prepare new studies aimed at strengthening Cuchillacocha Lake, which at that time spanned 170,437 m^2, had a volume of 3,014,000 m^3, and a maximum depth of 33 meters (Note: prior to the current system of regional government, various corporations were in charge of regional development).



Aerial and ground views of Cuchillacocha Lake's dam, completed in 1974. Right photo: César Portocarrero

Given the low existing dam (4 meters tall), the Glaciology Unit built additional safety works. The first step was to lower the lake's surface level by 10 meters, which entailed evacuating about 1.6 million m^3 of water. Next, they built a covered conduit and over it erected a 16-meter-high earth dam to contain future wave surges from ice avalanches. Inflow and outflow canals were added for the covered duct. In addition, they built bridle paths and semi-permanent camps for field workers. The work was completed in 1974.

Conclusions: This is one of five lakes above Huaraz that was re-treated because of concerns following the 1970 earthquake. Engineers believe that Cuchillacocha Lake is a role model for the effectiveness of the well-established formula developed in Peru: reduce lake volume, install a large drainage conduit, and build a safety dam over the conduit that provides a high freeboard against possible waves resulting from avalanches striking the lake.

5.13. TULLPARRAJU LAKE

Location: 4,283 meters, east of Huaraz, at the foot of Nevado Tullparaju, on the west side of the Cordillera Blanca.

Risk: Threatened by hanging glaciers. The lake's volume has increased 10-fold since 1974.

History of work: A threat to Huaraz, Tullparraju was among the first lakes to be treated following the 1941 flood from Palcacocha. In 1942, the lake's surface level was lowered by 18 meters with a V-shaped open cut. In addition to the open cut, a tunnel was drilled into the moraine so the lake wouldn't rise.

The terminal moraine is relatively stable because its principle component is a clayish material that resists erosion. However, its steep lateral moraines have slopes greater than 45 degrees, which are prone to landslides.

Tullparraju Lake showing its steep flanks and the hanging glacier above. Middle and right photos show the entrance and exit of the drainage tunnel. All photos from 1974: César Portocarrero

Over the years the tunnel developed numerous leaks, which prompted the Glaciology Unit to strengthen the drainage tunnel with concrete in 1974. The Unit also built a reinforced 10-meter-high earth dam above the tunnel to counteract possible glacier wave surges caused by avalanches or landslides.

The glacier tongue is melting and retreating, leaving behind an ever-larger lake. In 2013, the volume of the lake was 10 times the volume it had been in 1974.

Conclusions: As in the case of Palcacocha, a retreating glacier is leaving behind a growing lake. This requires careful monitoring, despite the lake's initial treatments in the 1940s. The lake's rapid growth in volume suggests that the current capacity of the safety works be carefully examined, including potentially adding an early warning system.

5.14. SHALLAP LAKE

Location: 4,260 meters, at the head of Shallap Valley, about 20 kilometers directly east of the city of Huaraz, on the west side of the central Cordillera Blanca.

Risk: After the 1970 earthquake, the Glaciology Unit deemed this lake a serious threat due to its high volume, small diameter drain pipes built in 1942 (which could easily clog with ice), low height of its 4-meter safety dam, and conditions on the adjacent San Juan Glacier.

Constructing the Shallap Lake safety dam and water channel in 1973 and the completed work in 1974. Photos: César Portocarrero

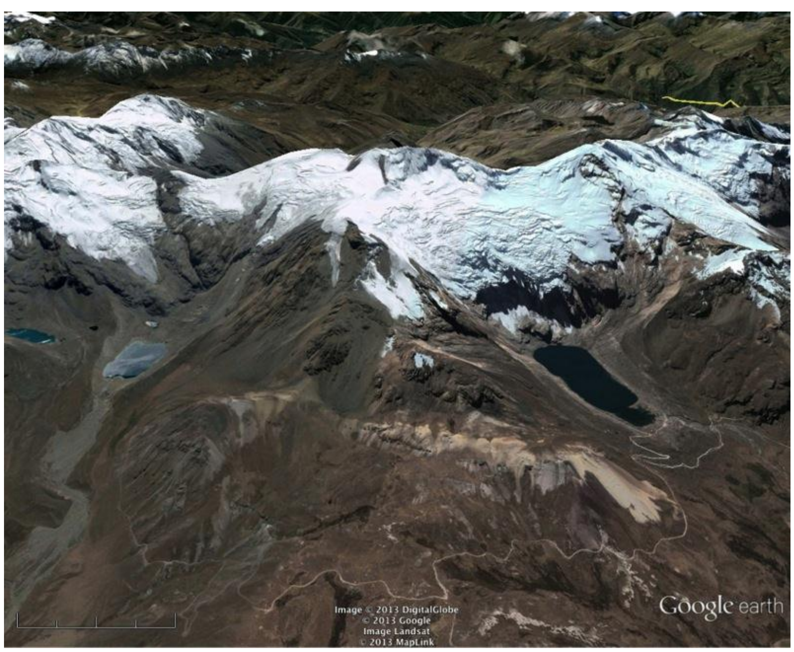
History of work: Shallap Lake's water level was lowered 8 meters in 1948. In 1951, two 42-inch(1,067 millimeter)-diameter steel pipes were installed to drain the lake. A 4-meter earth dam was added in 1952. After the 1970 earthquake, studies determined the lake to be 720 meters long and 320 meters wide, holding 4.7 million m^3 of water. The natural dam consisted of two high lateral moraines and a lower terminal moraine where the 4-meter-high dam had been built. In 1972–1974 the Glaciology Unit lowered the water surface by 10 meters and built an 80-meter-long covered passage, including a steel pipe beneath an earth dam and masonry channels. As in other cases, the artificial dam was built with a waterproof core and masonry walls.

The retreating glacial tongue above Shallap Lake in 1974, 1980, and 2010. Photos: César Portocarrero

Conclusions: Today, the glacier's tongue is far from the lake and the lake does not present a threat to the city.

5.15. LAZO HUNTAY LAKE

Location: 4,300 meters, Lazo Huntay and Chuspicocha lakes are in the Cordillera Huaytapallana, in the province of Junín, in central Peru.



Chuspicocha Lake (left) and Lazo Huntay Lake (right) in the Cordillera Huaytapallana, central Peru.

Risk: A small set of rapidly retreating glaciers can drop ice into the lakes.

History of work: Two alluvial events took place here in recent decades: one in 1969 from Lazo Huntay Lake, and the other in December 1989 from Chuspicocha Lake.

The 1969 GLOF from Lazo Huntay Lake was triggered when ice from a hanging glacier fell into the lake, producing a hydrodynamic thrust that launched a wave that destroyed the lake's stone masonry and its concrete dam (the dam had been built to store water, not for safety). This led to a large outflow of water that destroyed everything along the downstream basin. The original avalanche was likely triggered by an earthquake that took place in the vicinity of Mount Huaytapallana, where there is an active fault line.

In 1977, the Glaciology Unit initiated work (with support from The National Institute of Civil Defense of Peru) to partially drain the lake. Then, in early 1990, the Glaciology Unit recommenced work to complete the project by further lowering the water level, building an exhaust duct, and installing a dam.

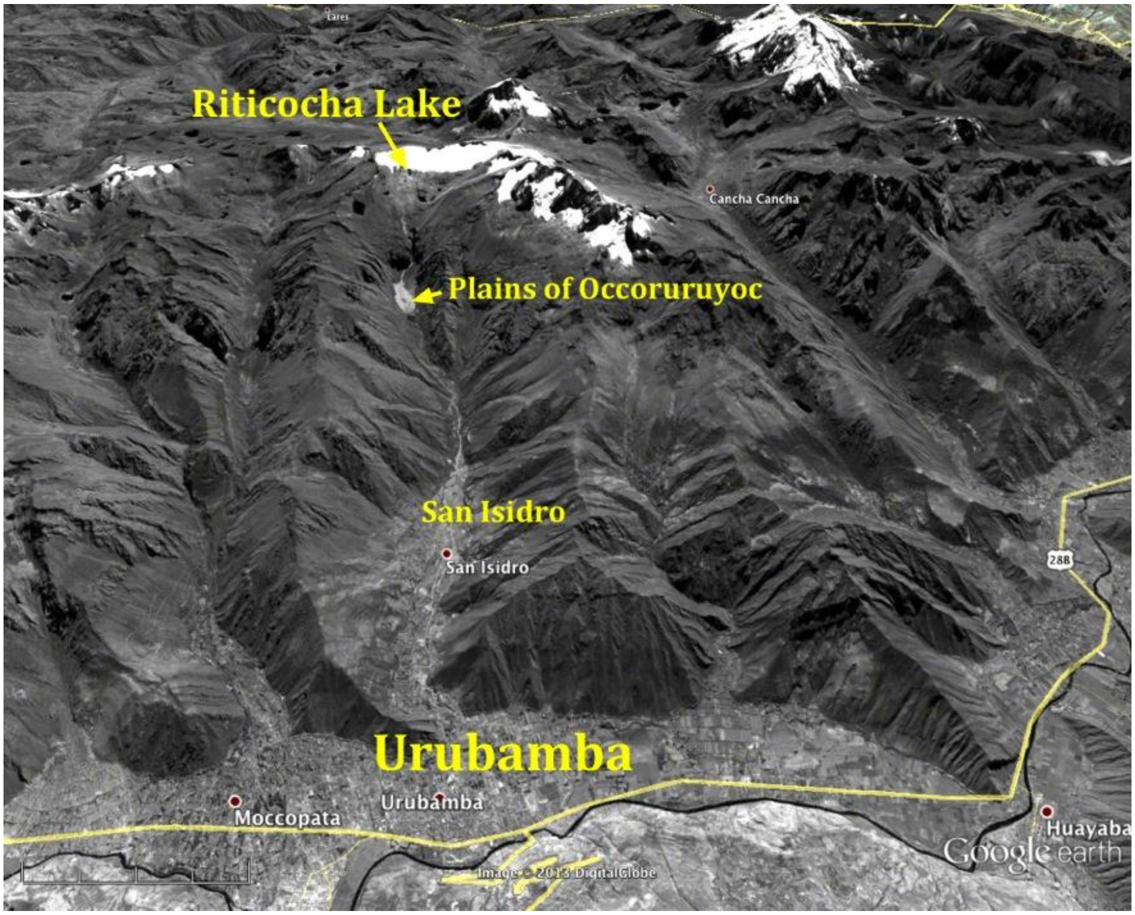
Lazo Huntay Lake showing the still-massive hanging glacier in 1990, and the newly completed safety works in 1990. Photos: César Portocarrero

Many locals in Huancayo (population 500,000) objected to lowering the lake because the Shullcas River basin, whose headwaters are in the Huaytapallana Mountains, suffers from continued water shortages. Water stress has long been a challenge and it appears to be growing more acute as the glaciers shrink–a problem understood well by locals.

Conclusions: In this case, there is a strong pull between physical safety and water supply. Water resources in the Shullcas River basin have become so critical that people focus on water shortages rather than on disaster risk management. The two need be managed on a case-by-case basis, balancing risk from floods with the need for water storage.

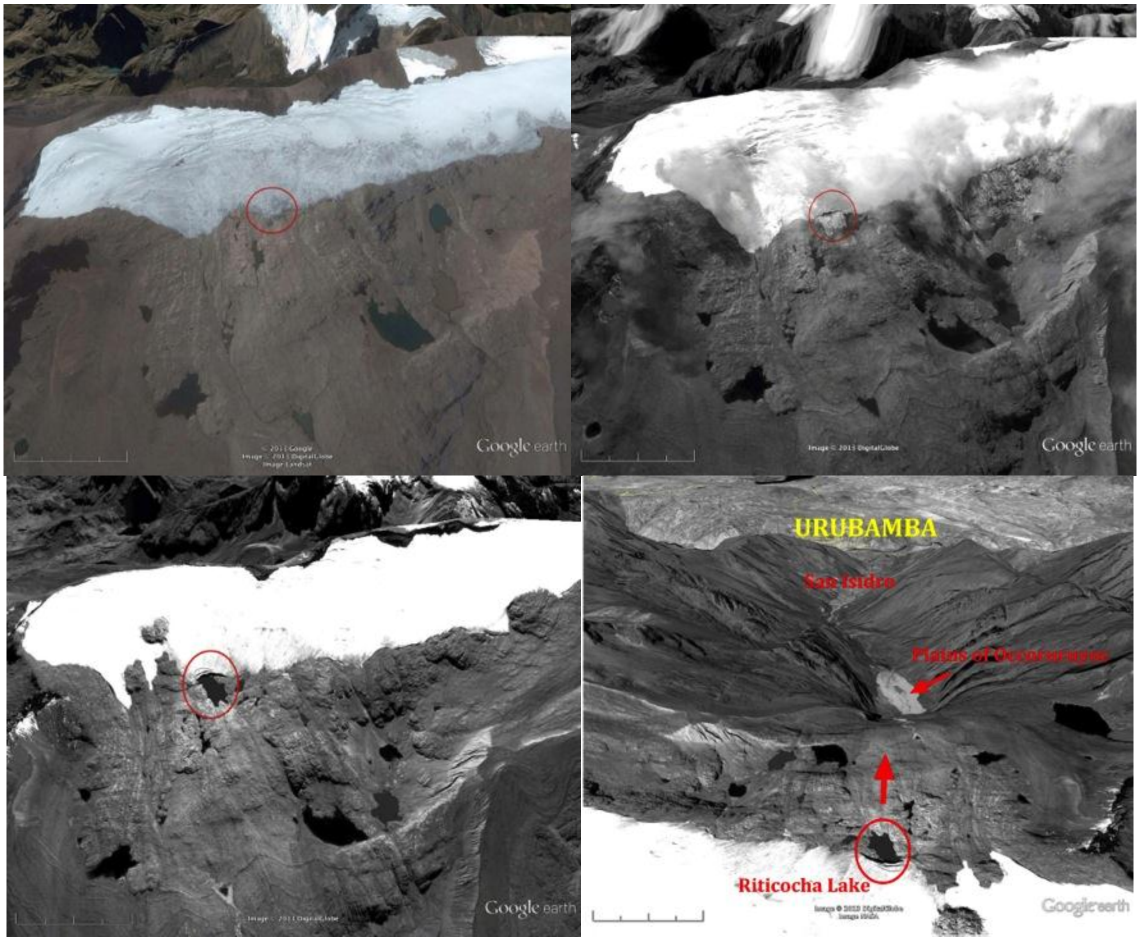
5.16. RITICOCHA LAKE

Location: 4,756 meters, at the foot of Mount Chicón, in the Upper Río Chicón River, in the Cordillera Urubamba of central Peru. Local communities in the catchment area include San Isidro de Chicón, Yanaconas Chichubamba in the Chicón River basin, and the city of Urubamba. The nearest community is San Isidro de Chicón, which can be reached by a dirt road starting in Urubamba and then continuing on foot for five hours to the base of Nevado Chicón.

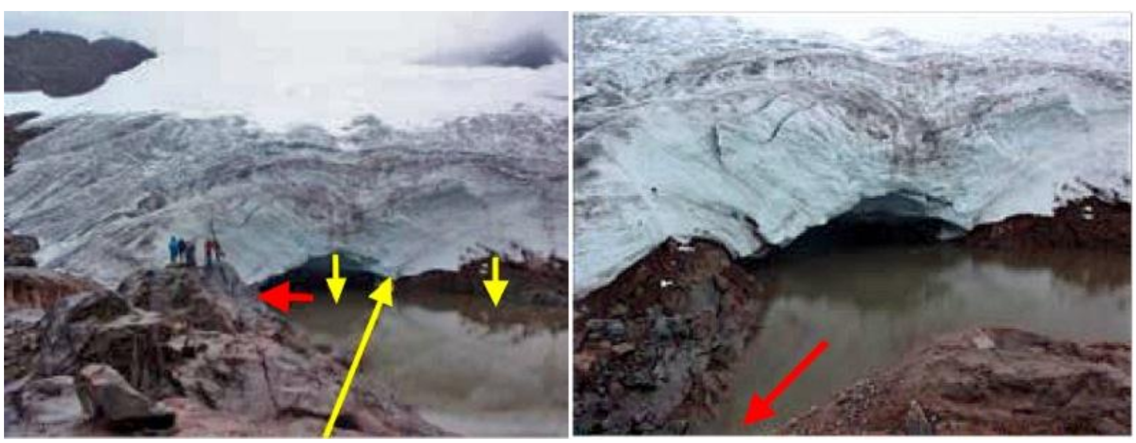


Riticocha Lake and its trajectory into Urubamba in 2012. Note: All local Google Earth 2012 imagery (the most recent imagery that was available in 2013) was in black-and-white.

Risk: The geology of the Riticocha Lake basin consists of very strong intrusive rock, ensuring that the newly emerged glacial lake's dam will not break. However, comparisons of photos taken in October 2010 with photos taken in April 2012 reveal significant glacial retreat during this two-year period that has left an arch of ice over the lake. Such cavitation results from the temperature gradient between the lake water and the ice above. If this arch collapses into the lake it will create a wave. It would also create a temporary ice dam, through which water will eventually break loose into the Chicón River, leading to another flood. The danger could grow after the glacier's current terminus has collapsed and melted because the retreating tongue would then turn into a hanging glacier. Momentum from falling ice could create a larger wave than from ice collapsing close to the lake.



The emergence of a new glacial lake. Top left: 2007 imagery and only the tip of the lake emerges. Top right: 2008 imagery and about a third of the lake has emerged. The bottom two images are from 2012.



View of the glacier arch over the lake on 23 April 2012. This ice may collapse at any time. The yellow arrows show the arch and the direction in which the glacier may collapse. The red arrows show the direction that Riticocha Lake drains at present. Photos: César Portocarrero

History of work: Riticocha Lake, lying outside the heavily researched Cordillera Blanca, does not have a long history of work. Instead, it presents an example of emerging risks.

Urubamba is the main city in a fertile valley with a mild climate. Corn, potatoes, and fruit are grown here in what is often called the "Sacred Valley," the "Pearl of the Vilcanota," or the "Archaeological Capital of Peru" due to its many archaeological sites. High above, in the upper Chicón basin, glaciers make the mountain weather cold and windy.

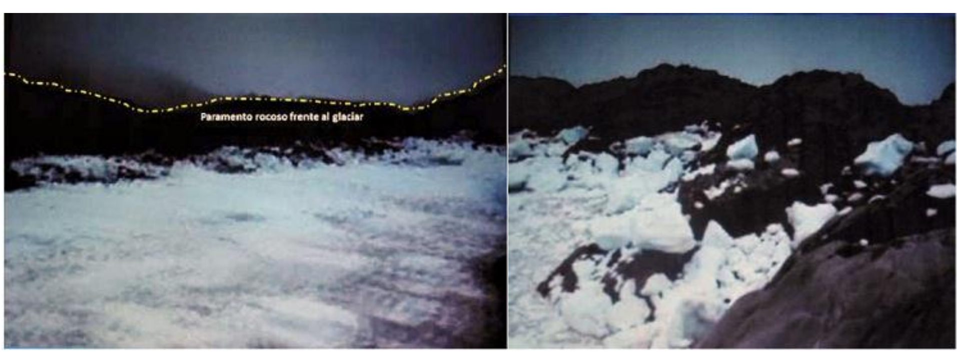
The Urubamba Valley lies at roughly 2,900 meters on an alluvial fan of moderate to low slopes with alluvial terraces on both banks of the Vilcanota River. Its tributary, the Chicón River, flows through a long, narrow valley bordered by very steep to moderate slopes. In its upper reaches, the topography is steep and abrupt with scattered lakes at different levels. With a summit height of 5,530 meters, Mount Chicón is the main glaciated peak in the upper reaches of the Chicón River basin. The distance between the mountain's glacial lakes and the nearest rural town is approximately 8 kilometers, and another 3 kilometers to the Urubamba Valley. In 2007, the local population was 56,685.

According to a 1989 glacial inventory (Ames, et al., 1988), the Urubamba Cordillera spans 41.5 km^2, with 90 glaciers classified according to the rules of the World Glacier Inventory. By 2013, rapid glacial retreat has shrunk the glaciers by least 30 percent, leaving a surface area of approximately 29 km^2 (author's unpublished calculations). The tremendous altitude differential between the lakes and the lowland creates the opportunity for stored potential energy (in the form of glacial lakes) to turn into violent kinetic energy (in the form of debris-filled floods).

The upper basin of the Chicón River shows evidence of historical alluvial phenomena, and townspeople in Urubamba are aware of past floods from glacier activity on Nevado Chicón. A flood destroyed parts of Urubamba as recently as 1942. Though the cause is unknown, the flood may have been triggered by an avalanche falling into a glacial lake. As often happens following natural disasters, homes and businesses were rebuilt in areas that could once again turn into alluvial channels (Carey, 2010).

On October 17, 2010, a large flash flood of the Chicón River damaged small towns as the water descended to the city of Urubamba. Investigations revealed that the flash flood was a GLOF from a new lake that had appeared at the foot of the Chicón Glacier: Riticocha Lake. Videos taken from helicopters revealed blocky fragments of ice on rock walls near the lake, indicating that one or more large waves had deposited them. It appeared that an original mass of water had triggered a second, lower lake to also be partially emptied.

Top row: Photos from the flood of the Chicón River in San Isidro and Urubamba resulting from the Riticocha GLOF on 17 October 2010. Middle row: Debris and flood lines on walls in Urubamba in 2010. Lower right: The path the Chicón River took through Urubamba in 2010. Top row photos: Municipality of Urubamba. Other photos: César Portocarrero



Waves deposited these large ice fragments high on Riticocha's rock walls. These photographs were taken a few days after the event and were taken during daylight, but are dark because it was captured from video. The dashed yellow line indicates the edge of the glacier. Photos: Urubamba Civil Defense

Such heavy destruction leads scientists from the Cusco Civil Defense to believe that the volume of the GLOF was larger than the volume of the present lake. Clues include the magnitude and size of transported rocks, the volume of debris, and the boulders that reached the town of Urubamba. The floodwater's destructive power was increased by recent road building activities. Construction had loosened the earth and construction debris, including broken tree trunks, had been dumped into the riverbed.

The lake's volume is currently estimated to fluctuate between 80,000 and 100,000 m^3, its maximum length is between 150 and 200 meters, its width is slightly more than 100 meters, and its depth is approximately 10 meters.

Conclusions: During a visit in April 2012, the author and other scientists and engineers (invited by the mayor of Urubamba) observed that the risk of ice avalanches falling into the lake was extremely high. The team concluded that Riticocha Lake is in urgent need of mitigation work. The author was charged with writing a report regarding diagnostics and recommendations (unpublished). The recommended steps illustrate standard procedures that have proven effective in Peru:

1) Establish adequate access to the lake by improving the bridal path. The current bridle path to Riticocha Lake is in very poor condition and will need to be repaired and rebuilt in its entirety, with appropriate signs to allow field visits at any time. Better bridges are also needed for crossing streams, ensuring the safety of personnel. In areas where the slope of the bridle path is very steep, weatherproof ropes as hand lines are recommended to be installed.

2) Investigate the lake's basin, including its dimensions, area, and volume at different depths (i.e., conduct a thorough bathymetric survey). Incoming flows to the lake and outflows should be gauged in order to determine the design and capacity of temporary siphons.

3) Use light drain pipes for reverse siphoning to reduce the lake's water level by 6 meters. Continue lowering the water level according to the characteristics of the chosen drainage channel or tunnel.

4) Build a drainage channel or tunnel to prevent the water level from rising again.

5) To further reduce the risk to Urubamba from Riticocha and other emerging glacial lakes, investigate the technical and economic possibility of building additional works (such as catchment dams) in the outlet mouth of the Occoruruyoc basin, which at one time was probably a glacial lake that ruptured its retaining moraine.

6) Improve and maintain the existing early warning system. Effective early warning systems require a participatory process including workshops and other meetings with the local population. Technical solutions on their own are not useful in early warning systems.

7) Because the Riticocha Lake is only 10 meters deep, there is the possibility of permanently emptying it if a cost-effective method can be devised. Permanently draining the lake would require that a channel or tunnel be cut into the bottom of the lake. This must be done very carefully because carving through hard rock with explosives could further destabilize nearby fractured glaciers. However, the end result would be much safer than retaining a lake of any size.

8) In addition to engineered safety measures, the populations of rural and urban areas in Urubamba and along the Chicón River should be organized and trained to understand the hazards of glacial lakes. In order to reach the maximum number of residents and to increase civil awareness, organization and training should be done through schools and other public educational and civil institutions.

New lakes are forming at the foot of glaciers throughout the Cordillera Urubamba. The damage resulting from the Chicón River's flood demonstrates the need for ongoing monitoring of these lakes and glaciers. Setting up a Glaciology Unit in Cusco would considerably assist this process.

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