MODELING A GLACIAL LAKE OUTBURST FLOOD (GLOF) FROM PALCACOCHA LAKE, PERU

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INTRODUCTION

Available data indicate that glaciers are undergoing a process of accelerated shrinking due to human intervention in the environment (IPCC, 2007). The biggest concentrations of ice sheets are located in Antarctica and Greenland. On the other hand glaciers in South America represent just 3 cm of the sea level. Even though the make up a small proportion of global ice cover they are critically important for human uses, including domestic, agricultural and industrial uses, particularly in the equatorial tropical and subtropical latitudes (Casassa et al., 2007) since the glaciers in tropical latitudes have a buffer effect over the runoff.

Glaciers in the Andes of Peru provide fresh water for arid western Peru during the dry season when little or no rainfall occurs (Vuille et al., 2008). The west coast of Peru uses the water coming from the high mountains for agricultural, domestic and industrial purposes. For example in Peru the main source of electricity generation is hydropower, representing 80% of the electricity in the country (Vergara et al., 2009).

Georges (2004) cited by Vuille et al. (2008) estimated that the glacier-covered area in the Cordillera Blanca range of Peru had decreased from 800-850 km^2 in 1930 to 600 km^2 at the end to the 20^{th} century. Racoviteanu *et al*. (2008) found 571 glaciers covering an area of 569 km^2 and experiencing a decrease in glacier area of 0.68% per year over the thirty-three year period 1970 – 2003, representing a 22.4% decrease in area over that period.

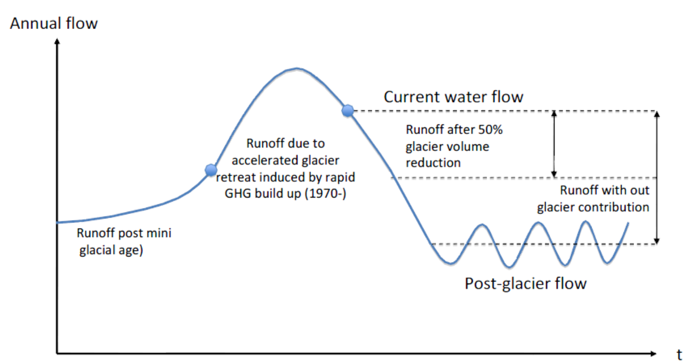


Figure 1: Impact of changes in glacier mass on runoffs (Source: Vergara, et al. 2009)

Figure 1 shows the general evolution of runoff due to glacier recession. Accordingly, an increase in runoff is expected during the first part of the retreat and an abrupt diminution of runoff in the latter part of the process. During the early stages, when runoff increases, there is a high risk of glacial lake outburst flooding of downstream zones adjacent to rivers. For example, Lake Palcacocha in Peru (Figure 2) was declared to be in an emergency state because its level is higher than the safe level (Diario La Republica, 2010). The glacier above of the lake is has a very high . The risk now is that in the event of a landslide or ice avalanche into the lake, the moraine could fail, abruptly releasing a huge volume of water from the lake and creating a GLOF (Instituto Nacional de Defensa Civil, 2011).

In order to reproduce the behavior of an eventual GLOF at Lake Palcacocha the aim of this study is to perform a 1D simulation of a GLOF using HEC-RAS for the hydraulic calculations and HEC GeoRAS for visualization. The study considers the GLOF to be composed of pure water, in this initial step, due to the difficulty of the problem analyzed and the complications of debris flow modeling.

Figure 2: Palcacocha Lake (photo by Colette Simonds).

GLACIER LAKE OUTBURST FLOOD (GLOF)

A Glacier Lake Outburst Flood (GLOF) is a sudden release of a huge amount of water, many orders of magnitude higher than the normal flow, from a lake formed at the snout of a glacier (Figure 3) due to a breach of the moraine dam (Carrivick, 2006). According to Awal et al. (2010) it is common to find moraine dammed lakes and GLOFs in different glacierized regions. In addition, Osti and Egashira (2009) point out that even though there is a great urgency to evaluate the impact of GLOFs and validate models that represent such events, it is difficult to obtain good approaches because of the lack of information. Attention has been primarily focused on past events, and satellite image information, but not on the hydrodynamic characteristics and continuum mechanics of the floods (Osti and Egashira, 2009). GLOFs can cause los of life as well as losses in expensive infrastructure. According to Richardson and Reynolds (2000), cited in Bajracharya et al. (2007) and Osti and Egashira (2009), GLOFs represent one of the most significant glaciers hazards related to glacier recession and increases in temperatures due to climate change. GLOFs can affect fragile mountain ecosystems as well as economic activities due to the large magnitude of the flow (Bajracharya et al. 2007). For example on December 12, 1941 a GLOF occurred from Lake Palcacocha in Peru (Figure 2) flooding the city of Huaraz and killing more than 5000 people and destroying infrastructure and agricultural land all the way to the coast (Carey 2010). Many other regions with glaciated mountain ranges have experienced GLOF events, from Canada and Italy to Nepal and Peru (Bajracharya and Mool, 2009; Carey, 2005, 2010; Clague and Evans, 2000; Huggel et al. 2003; Kääb 2005; Richardson and Reynolds, 2000).

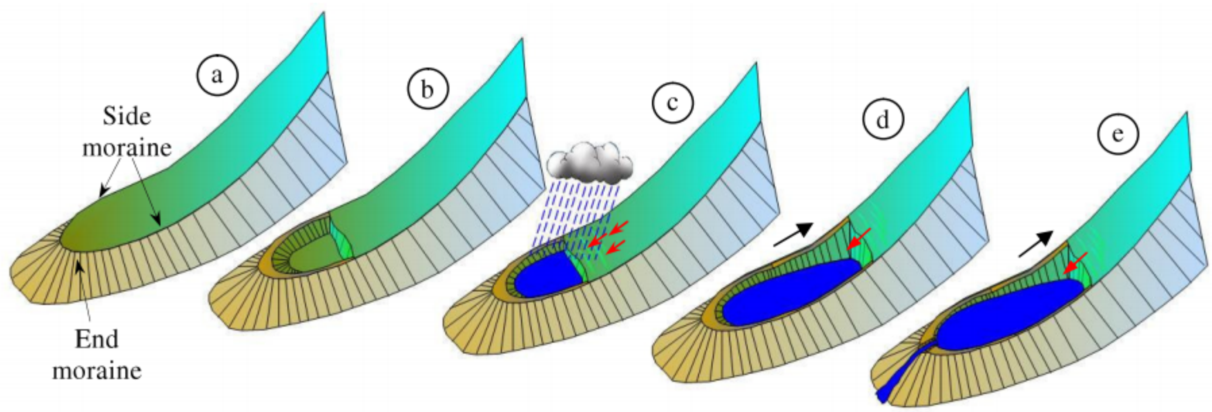


Figure 3: Formation of moraine-dammed lake (Awal et al. 2010)

BACKGROUND

GLOF Trigger mechanisms

In order to breach a moraine, a trigger mechanism is needed. There are many different trigger mechanisms, some examples are: waves generated by a snow or rock avalanche into a glacial lake, melting of the ice core of a moraine damming a lake, overtopping of a moraine due to intense rain or snow, earthquakes, etc. Even with the diversity of trigger mechanisms, waves produced by avalanches of ice and rocks are the main cause of breaches (Bajracharya et al. 2007). In a study of 20 GLOFs with identified trigger mechanisms, Bajracharya et al. (2007) concluded that 80% of the dam breaks where due to avalanches into the glacial lakes.

GLOF outflow hydrographs are functions of the trigger mechanism, overtopping due to wave generation from ice avalanches in most cases (75%). Additionally, the shape of the GLOF hydrograph is a function of the moraine breaching process which is a function of the nature of the wave produced by an avalanche. Therefore it is important to identify the characteristics of avalanches, magnitude and location, in order to have a better understanding of GLOF characteristics (Bajracharya et al. 2007).

Dam Characteristics - In addition to trigger mechanisms, a GLOF hydrograph is highly dependent on the characteristics of the moraine dam. In this section, some of the results obtained by Awal et al. (2010) in an experimental study on glacial lake outburst floods due to waves overtopping and eroding moraine dams are discussed. The effects of the shape of the moraine, the freeboard and the slope of the upstream side of the dam are considered.

Moraine shape - Awal et al. (2010) compared triangular and trapezoidal dams, in both cases erosion of the dam started at the outer face of the dam. Triangular faces produce earlier and higher hydrograph peaks.

Freeboard - The magnitude of the waves generated by an avalanche falling into a lake depends on the size of the avalanche as well as the volume and depth of the water in the lake at the time of the avalanche. If the freeboard is small, it is more probable that the wave will overtop the moraine. Therefore, if the freeboard is small the dam is be more vulnerable to breaching.

Material of the moraine - According to Awal et al. (2010), the shear stress due to suction is an important factor of the velocity in a breaching dam. Also the evolution of the breach is dependent on the particle size distribution, friction angle, cohesive strength, and non-homogeneity of the dam and its materials.

Slope of the inner face of the dam - The slope of the inner face of the dam is another factor that influences the failure mode of a moraine. The probability of dam failure increases with the slope. Smaller slopes result in later hydrograph peaks. Smaller volumes are drained from the lake when the slope is smaller because the depth of the breach will be smaller.

STUDY AREA

Location

This study aims to estimate the impact of a potential GLOF from Lake Palcacocha located at an elevation of 4,567 m in the Quillcay catchment of the Cordillera Blanca in Peru. A GLOF from this lake may reach the city of Huaraz, as happened in 1941 with devastating consequences. The lake flows into the Quebrada Cojup, which drains to the Quillcay River. The Quilcay River passes through the City of Huaraz giving its water to the Santa River, which is the main stream of the basin (Figure 4). Lake Palcacocha is of special interest since the city of Huaraz was devastated by a GLOF released from the lake on December 13, 1941 killing more than 5000 people (Vilimek et al. 2005, Carey, 2010). In 1941 the lake had an estimated volume of 10 to 12 million m^3 of water (Report of Hazard 003-12/05/2011, National Institute of Civil Defense of Peru). In 1974, safety structures were built in the moraine dam of the lake in order to maintain a safe level of water in the lake (Figure). The safe level of the lake has been estimated to be around 0.5 million m^3, however at the present time (2011) the volume is about 17 million m^3 (Table 1). Hegglin and Huggel (2008) concluded that at the time of their study Lake Palcacocha water had a high probability of reaching Huaraz since its volume was 3 million m^3. Therefore, with the current volume of 17 million m^3 there is no doubt that a GLOF would travel all the way down to Huaraz and cause significant damage and loss of life.

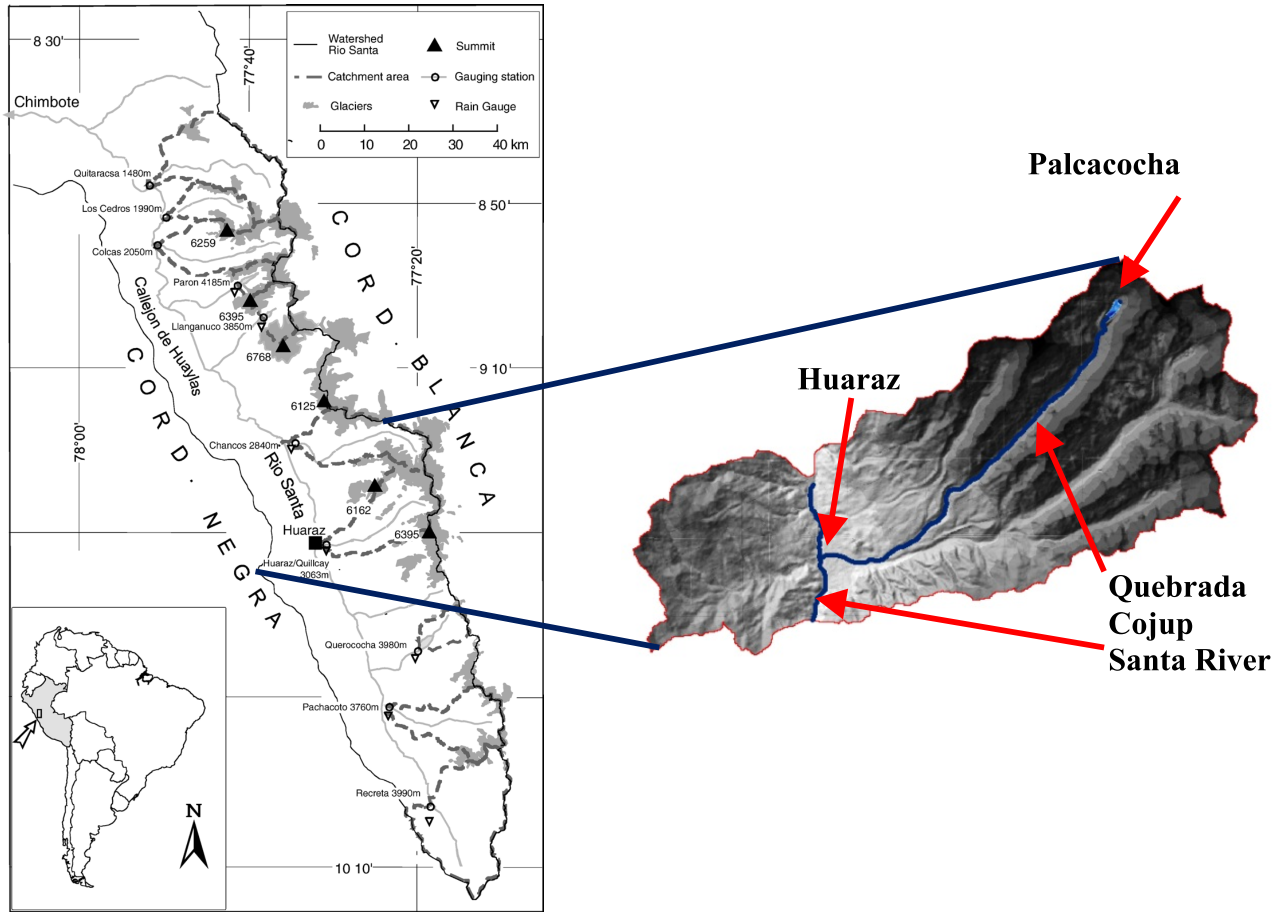
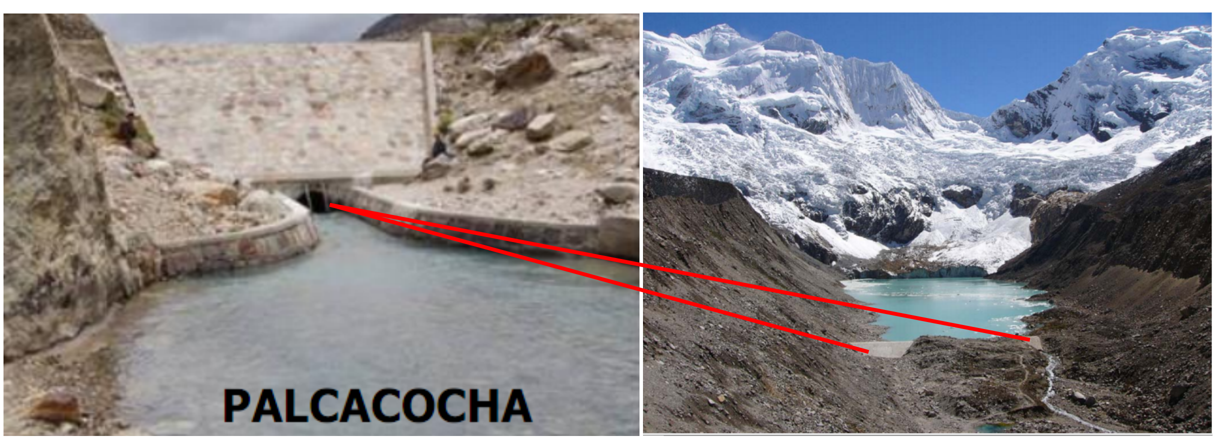


Figure 4: Map of the study area (Source: <<need to cite where the maps came from>>).



a) b)

Figure 5: a) Hydraulic structures for draining water from Lake Palcacocha. b) Front view of the Lake in September 2004 showing the two artificial concrete dams (photo by Z. Patzelt 2004 cited in Vilimek et al. 2005).

Table 1: Volume of water at Lake Palcacocha (Source: National Institute of Civil Defense of Peru).

Year	Wide x Length m	Elevation masl	Area m^2	Volume m^3	Maximum Depth m
1972	390 x 220	4567	66,800	579,400	14
1974	420 x 250	4566	62,800	514,800	13
2003*	120 x 350	4566	342,332	3,959,776	15
2009	1600 x 437	4566	518,426	17,325,207	73

* There is some question about the accuracy of the 2003 values since they seem to have been taken after the 2003 GLOF event (personal communication, C. Portocarrero, Aug 3, 2011).

Climate

Andean Tropical Glaciers

Around 70% of all tropical glaciers are located in Peru. The most extensively glaciated mountain range is the Cordillera Blanca (Figure 4), which hosts nearly a quarter of all tropical glaciers. In comparison with alpine glaciers, which have a period of ice accumulation during the cold season and a short period of ablation in summer, the glaciers of the tropical Andes experience, in their lower part, an ablation regime throughout the year. In the higher part of the tropical glaciers of Bolivia and Peru the strongest ablation period coincides with the summer months of the southern hemisphere (October-April), and in Ecuador it coincides with the equinox months (April-May and September). In addition, the annual oscillation of temperature in those latitudes is insignificant compared with the diurnal oscillation (Coudrain et al. 2005).

Climate change and glacier retreat

It is widely known that glacier retreat in the warming tropical Andes has accelerated significantly in the past few decades, including the area surrounding Lake Palcacocha (

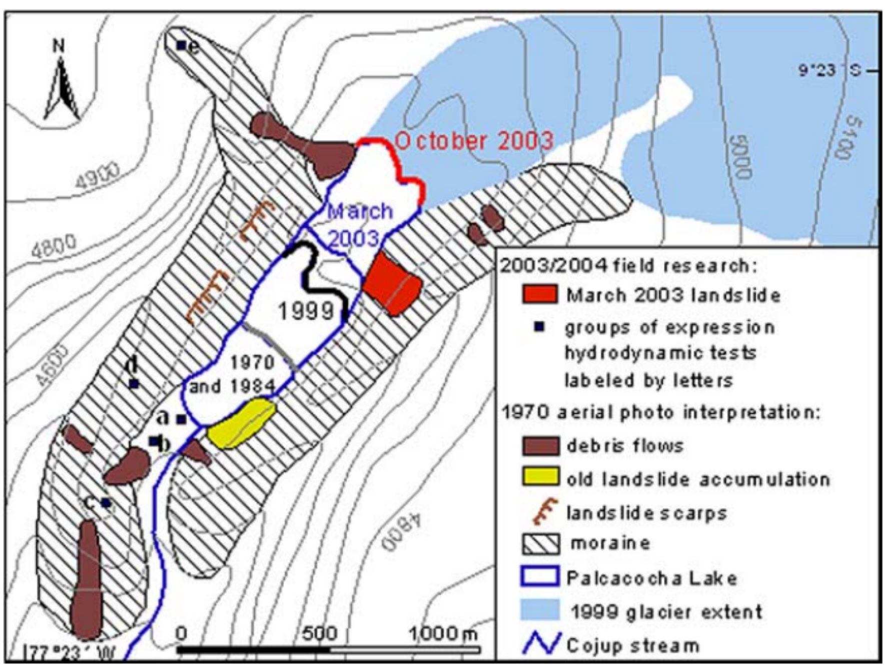


Figure).

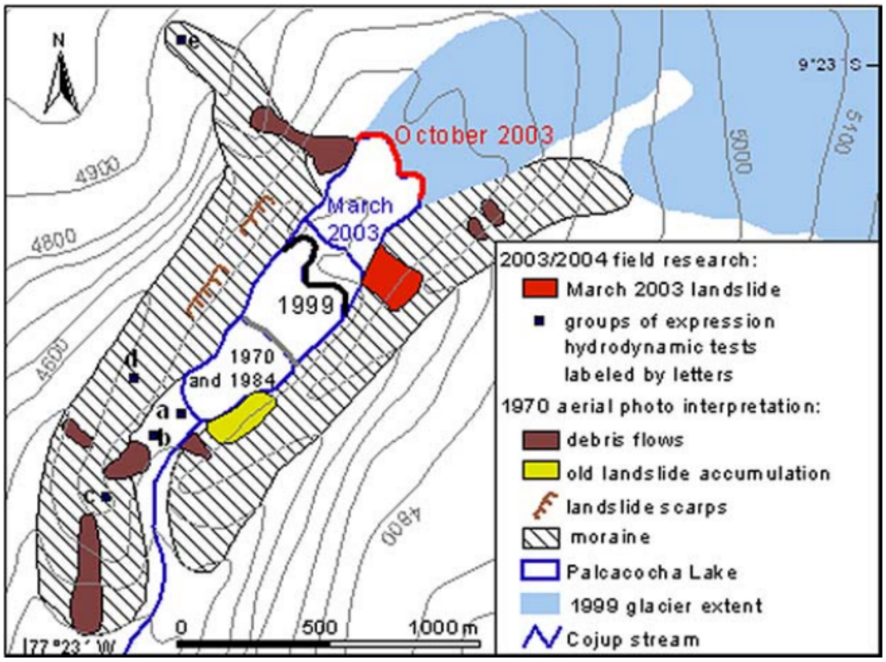


Figure 6: Glacial retreat history between 1970 and 2003 for Lake Palcacocha vicinity (Vilimek et al. 2005).

It is more difficult to relate the fluctuations of mass balance for tropical glaciers to climatic changes than for mid-and high latitude glaciers because they do not depend primarily of the fluctuations in local temperature, on the contrary the most important factors may be those that drive albedo. Vuille et al. (2008) pointed out that the temperature in the tropical latitudes will increase around 4-5 ^{o}C by the end of this century, but the consequences of this temperature increase on tropical glaciers are not easily predictable since temperature and sensible heat transfer do not play such a dominant role as they do for mid-latitude glaciers. Also the processes are more complex in the tropics because the increase in melting indicates a complex combination of factors related to the energy balance, such as temperature, duration of dry events, precipitation and humidity which control albedo, and melting/sublimation (Coudrain et al. 2005). Moreover radiative fluxes and turbulent latent heat flux appear to dominate the glacier surface energy balance (Vuille et al. 2008).

Relationship with regional-scale climate

Even though temperature is not the most important variable of tropical glacier energy balance, it plays an important role in the mass balance, because temperature is strongly related to other parameters that have a more direct relationship with mass balance, such as humidity. When the air is cold, it is wet and when the air is warm it is dry (Vuille et al. 2008). Even though temperature is not the driver in the glacier recession process; it may be used as an indicator of humidity. According to Vuille et al. (2008) "This behavior makes the attribution of mass balance variations to individual climate parameters more difficult, because years with increased accumulation are also commonly characterized by reduced melt, while ablation is usually enhanced in years when snowfall is already low."

Even though there is this correlation between temperature and humidity, precipitation is a better indicator of tropical glacier dynamics than temperature. There is a positive correlation between precipitation and glacier mass balance. In addition, there is a negative correlation between vapor pressure at the surface and glacier mass balance. If the vapor pressure is high the gradient of latent heat flux will be smaller, as a result sublimation will be limited and the available radiative energy will be consuming by melting, which is about 8.5 times more energy efficient than sublimation, causing higher overall mass loss (Kaser et al., 1996b, 2005; Wagnon et al., 2001; Sicart et al., 2005; Vuille et al., 2008).

ENSO effects

Andean glacier retreat has not been uniform throughout the 20th century. The glacier mass balance appears to be controlled by decadal climate oscillations driven by the El Niño Southern Oscillation (ENSO) mechanism. During El Niño events the temperature increases and the precipitation decreases in the tropical areas, as a result the glacier mass balance becomes negative. On the other hand during La Niña events temperatures decrease and precipitation increases, as a result the glacier mass balance becomes positive. According to Coudrain et al. (2005), intertropical glaciers may lose from 600 to 1200 mm of water equivalent during El Niño periods.

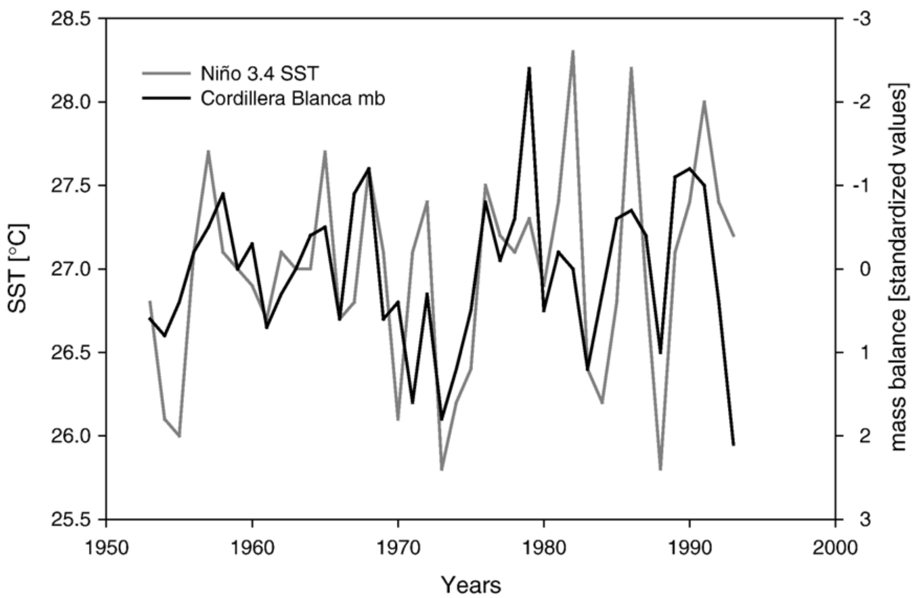


Figure 7: Correlation between annual (Oct.–Sept.) Cordillera Blanca mass balance time series in black (standardized values) and ONDJFMA Niño-3.4 index in gray (in °C). Years refer to OND part of the year; hence 1960 refers to 1960/61. Please note that scale for mass balance is reversed (Vuille et al. 2008).

Another indicator of glacier retreat acceleration in the tropical areas is that warm ENSO events have occurred with higher frequency during the last 20 years. Specifically the temperature has been abnormally warm for more than 15 years, while cold conditions were more frequent during the 1956 to 1976 period (Figure).

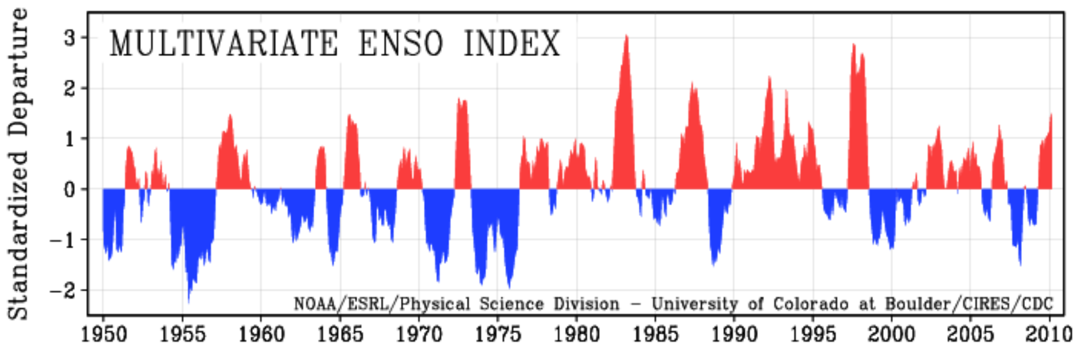


Figure 8: Multivariate Enso Index. (http://www.esrl.noaa.gov/psd/people/klaus.wolter/MEI/)

Projected Temperature Changes

According to Bradley et al. (2004) who analyzed mean monthly temperature from seven coupled atmosphere-ocean general circulation models, the temperature in the next eight decades will increase. Also larger increases in temperature are expected at higher altitudes. Coincidentally, glaciers in the subtropical areas are located in higher elevations; therefore these glaciers will experience higher increments of temperature.

GLOF MODELING

Physical Information

For this study, a 30m x 30m resolution digital elevation model (DEM) was used (ERSDAC, 2010). HEC-GeoHMS (USACE 2010b) was used in ArcGIS to delineate the river basin. Also, a drainage line dataset created by the Geographic-Military Institute of Peru was used to correct and verify the DEM information. That dataset provides, among other things, the streamline of the Cojup Creek and the Rio Quillcay considered in this study as well as the streamline of the Rio Santa.

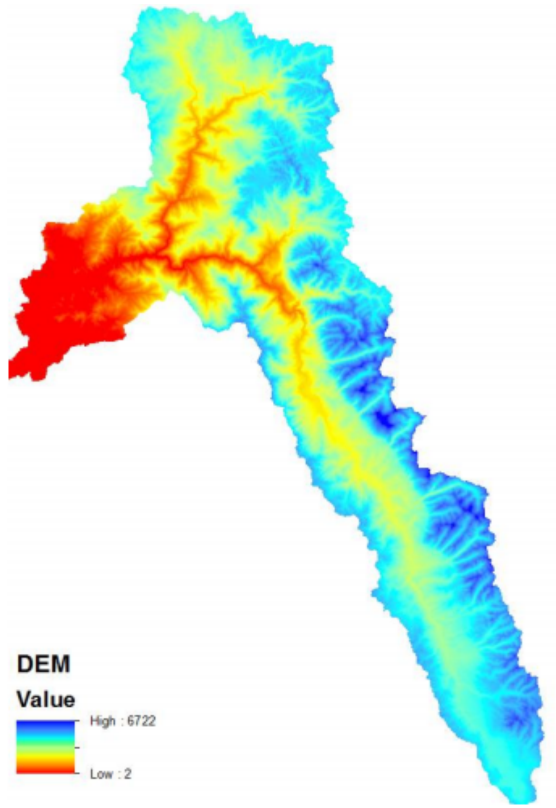


Figure 9: Digital elevation map of the Santa River basin at 30-m resolution

The delineated reach has a length of 22km from the Lake Palcacocha moraine to the Rio Santa at Huaraz. Due to the coarse resolution of the DEM the information obtained for the Rio Quillcay at Huaraz and the associated floodplain was not included since it was clearly inaccurate (Figure 4). The flow paths, banks, and Lake Palcacocha moraine (dam) were digitized using Google Earth. Then HEC Geo-RAS (USACE 2009) was used to extract 178 cross sections from the DEM.

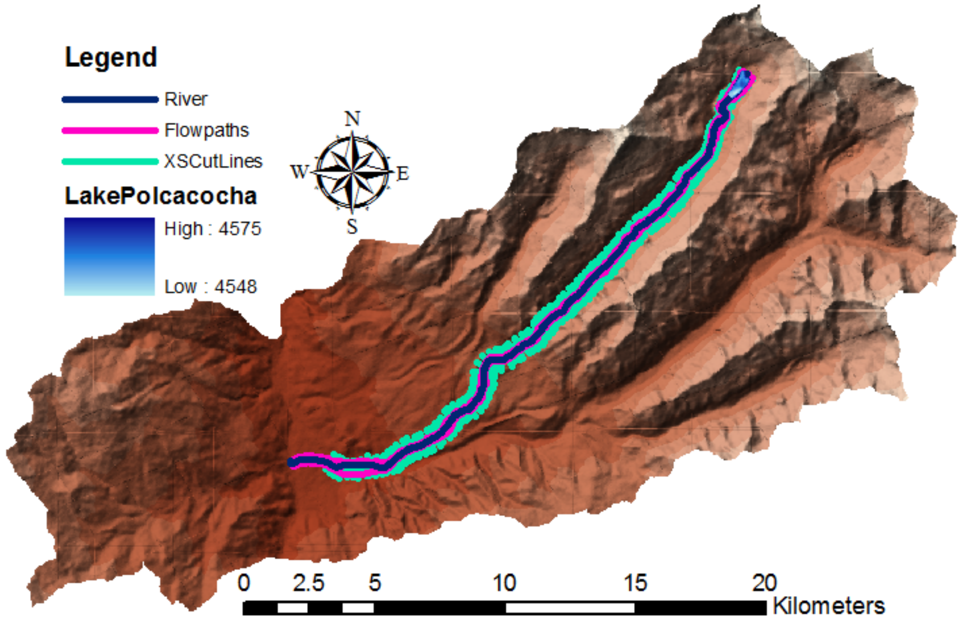


Figure 4: Output from HEC Geo-RAS.

Hydraulic calculation

HEC-RAS model has been used to perform the hydraulic calculations of the potential Lake Palcacocha GLOF. Due to the unstable nature of the dam breach process the model parameters were calibrated to achieve greater stability rather than accuracy in the solution, since the terrain data of coarse resolution (30m). HEC-RAS reference manual recommends DEM resolution of no more than 10m. The stability of the model is function of the distance between the cross sections and the time step used in the simulation. The minimum time step allowed in HEC-RAS is one second, which was used here. In addition cross section interpolations were performed in the locations where the solution becomes unstable.

As mentioned above, the current (2011) volume of water in Lake Palcacocha is about 17 million m^3. In order to calibrate the outflow hydrograph from the dam breach an empirical equation is used. For simplicity, Popov's relationship $Q_{max} = 0.0048V^{0.896}$ where Q_{max} (m^3/sec) is the peak discharge from the breach and V (m^3) is the volume of the lake (Popov, 1991 as cited in Huggel et al., 2002). The resulting peak discharge is 14,445 m^3/sec from the moraine breach. In order to obtain a similar value as a peak outflow in HEC-RAS, the dam breach was set as shown in Figure . The full formation of the breach takes 30 minutes. The breach is produce by overtopping since this is the most probable case. The depth of the breach is 35 m high, with a bottom width of 50 m. The river was considered wet at the beginning of the simulation with an initial flow in the river of 200 m^3/sec. Another important parameter is Manning roughness coefficient (*n*). Manning's *n* was considered homogeneous for the entire river with a value of 0.05. This value is recommended for mountain streams (Chow 1959).

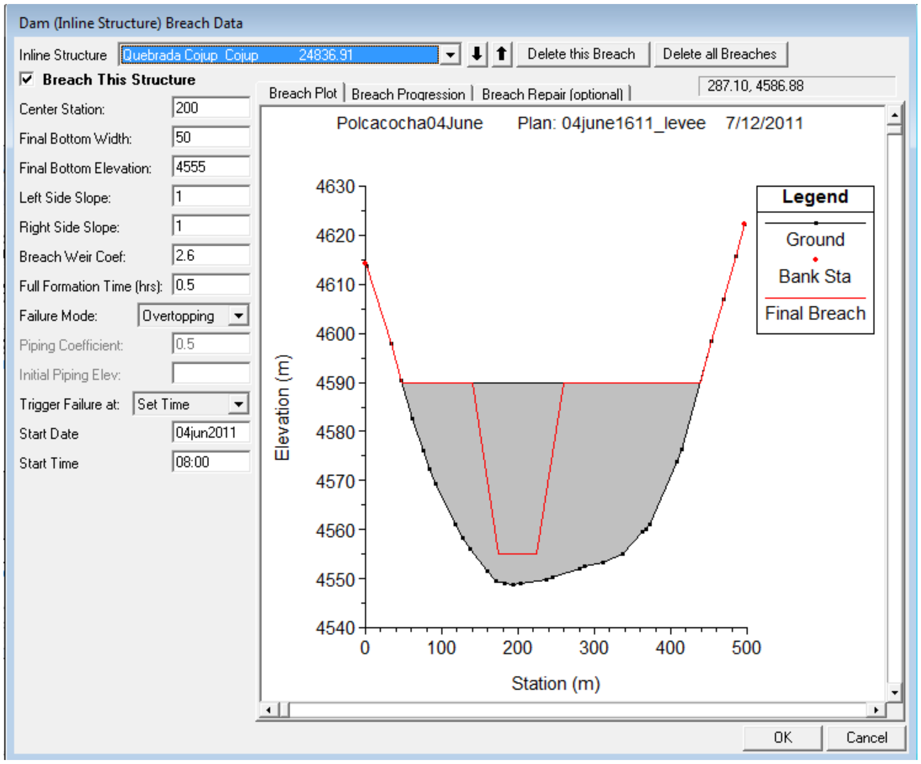


Figure 11: Dam breach input data.

RESULTS

As mentioned above, the time for the moraine to breach is 30 minutes. The outflow peak occurs 22 minutes after the start of breaching. The peak flow rate is 14,476 m^3/sec, which is very close to the peak calculated with Popov's equation. Figure 5 and Figure 6 show the water elevation and flow rate at the dam cross section and the last cross section in the Rio Quilcay downstream. The lag time between the peak flow at the dam and the peak flow at the downstream cross section is 20 minutes. Hence the dam breach wave traveled 22 km in 20 minutes (66 km/hr). The volume of water released from the dam is about 15.5 million m^3. Almost all of that water passed through the downstream cross section; therefore, there were not significant losses due to accumulation along the river. Due to the steeply sloped terrain, the flow is supercritical most of the time. Figure 7 and Figure show that the HEC-RAS calculations are consistent since the maximum water velocities agree with the higher slopes.

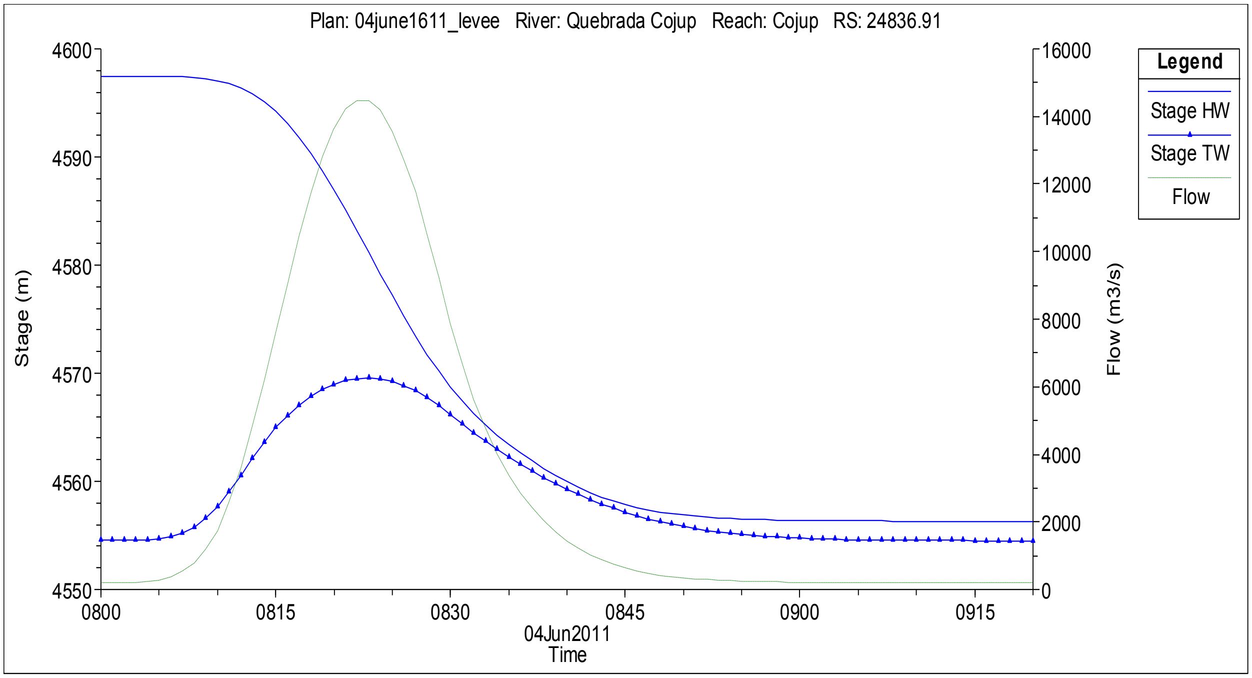


Figure 5: Dam breach hydrograph. HW: headwater, TW: tailwater

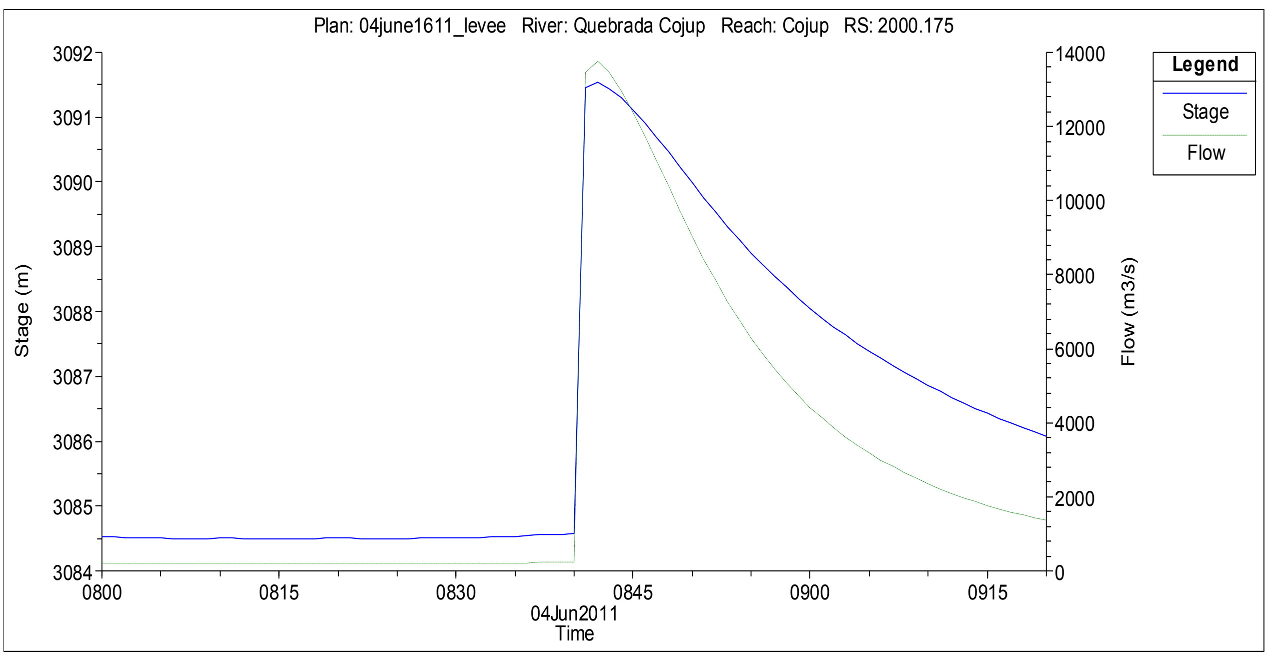


Figure 6: Downstream cross section hydrograph

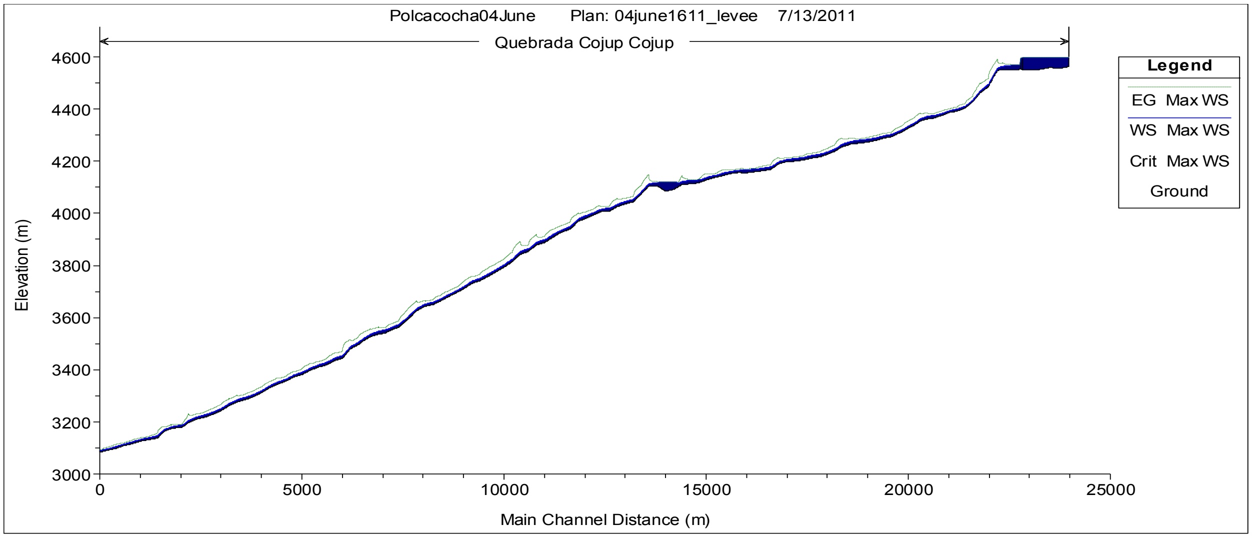


Figure 7: Longitudinal profile of the maximum flow.

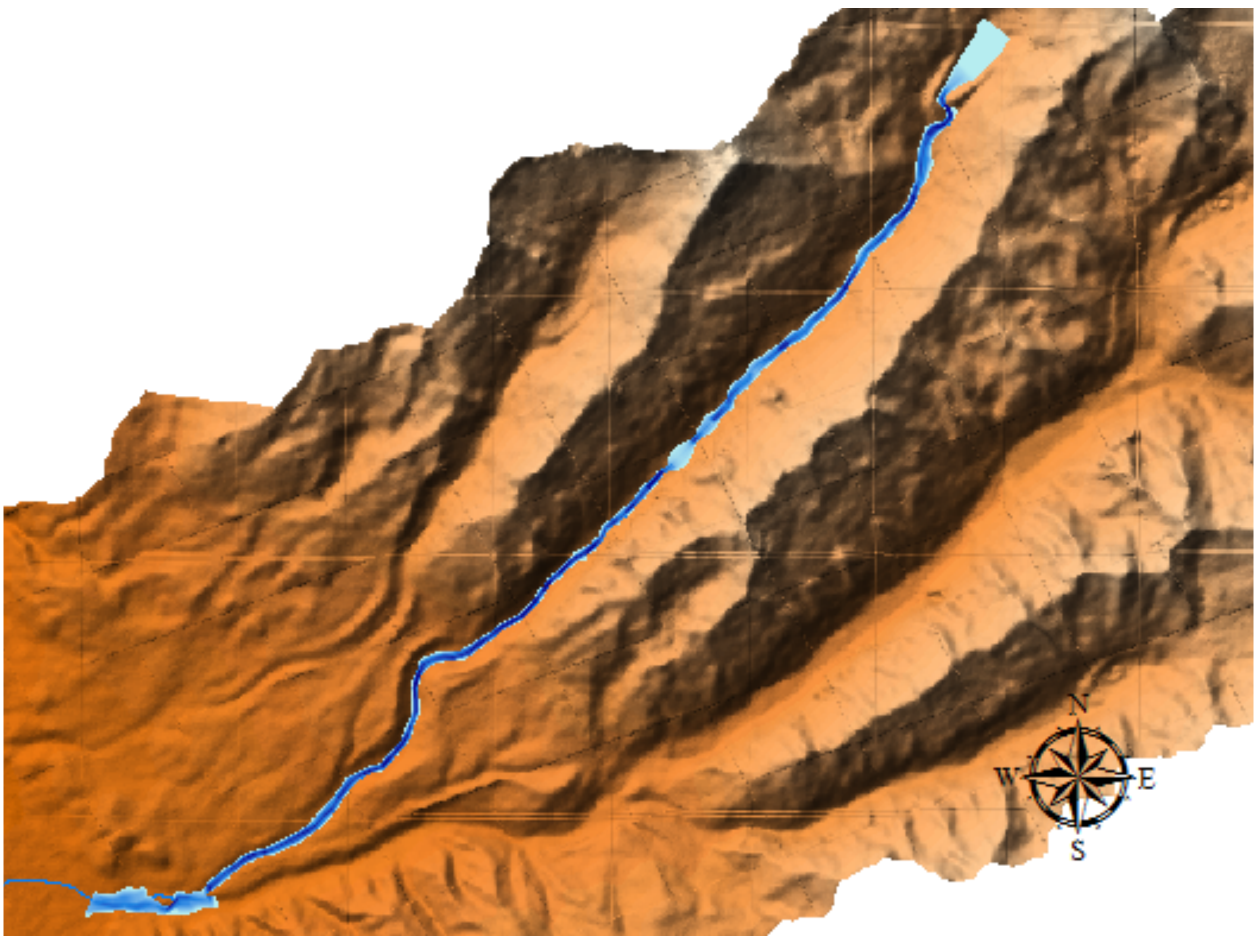


Figure 15: Aerial view of the maximum inundation.

CONCLUSIONS AND FUTURE WORK

This work was performed with little information. The results obtained are preliminary, without much calibration due to the lack of detailed terrain data. It is important, in order to increase the accuracy of the result, to obtain more detailed terrain data from surveys or Lidar. Paleoflood information would also be useful for calibration as well as terrain marks from the GLOF that occurred in 1941. Knowing the characteristics of the dam is important: materials, dimensions, slope of the wall and so on. The characteristics of the Quebrada Cojup are important, an adequate Manning coefficient needs to be estimated. In addition it is important to have terrain data for the city of Huaraz and the confluences of the Quillcay River and the Quebrada Cojup as well as the Quillcay River and Santa River. All of that information is the base for improving what has already been done. The next step for this work is to perform a simulation that includes the debris flow in order to obtain a more realistic solution for the GLOF problem. In addition, it is important to perform two-dimensional simulations and, less probable, three-dimensional simulations in order to have a more detailed representation of the problem. It is important also to investigate and perform simulations with different roughness models that may be applicable to GLOFs in regions with steep slopes. This is more complex numerically and will demand better information; therefore, it will be integrated into this study when the one-dimensional solution includes adequate input information. Finally, a vulnerability assessment should be carried out at the end of this work. In this study it was possible to determine that the flood wave takes 20 minutes to reach the city of Huaraz, which gives a time period for planning an evacuation. This would allow developing a zoning map of the city to be elaborated, or an alarm system in case an avalanche is detected and so on. At this point many questions for this work come along; this is just the first step.

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