S T U D I A G E O M O R P H O L O G I C A C A R P A T H O - B A L C A N I C A
VOL. XXXIX KRAKÓW 2005 PL ISSN 0081-6434
L A N D F O R M E V O L U T I O N I N M O U N T A I N A R E A S

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GLACIAL LAKE OUTBURST FLOODS IN THE AREA OF HUARÁS, CORDILLERA BLANCA, PERU

Abstract. Historical records proved repeating occurrence and extremely high damaging potential of glacial lake outburst floods (GLOFs) — local name aluviones, which are caused by outbursts of large amount of water from glacial lakes in the Cordillera Blanca Mountains. Archive sources as well as interpretation of SPOT and LANDSAT satellite images have been used to describe past history of GLOF´s in the Cordillera Blanca Mountains. The origin and evolution of glacial lakes and recent conditions influencing GLOFs hazard of selected lakes have been evaluated in respect to ongoing climate warming. Substantial enlargement of lakes surface areas were detected using ground measurements and satellite imagery. Contemporary risk imposed by natural hazards connected with glacial lakes on the regional capital city of Huarás, has been evaluated. The research has proved that the climate warming and deglaciation play significant role in the change of natural hazards conditions in high mountains.

Key words: glacial lakes, natural hazards, slope movements, flooding, Cordillera Blanca, Peru

INRODUCTION

Mountain range of the Cordillera Blanca, which is part of the Western Cordillera (Cordillera Occidental) is situated in the northern Peru. Cordillera Occidental is in this part of Andes divided into two major mountain ranges trending from the NW to the SE. This area belongs to the Ancash region, with the capital city of Huarás, which occupies the bottom of the Santa River Valley at the elevation of 3,080 m a.s.l. (Fig. 1).

Glacial lakes in Cordillera Blanca impose serious hazard on local settlements and in the past caused many times various natural catastrophes. Their overview published e.g. by M. L. Zapata (2002) shows that more than 4,300 people died in such catastrophic events in the 20th century. S. D. Richardson and J. M. Reynolds (2000) estimate some 32,000 victims of glacial lake outbursts in whole Peru during the same time period. On the other hand, glacial lakes are vital source of good quality drinking water and irrigation water for agriculture as well. Glacial

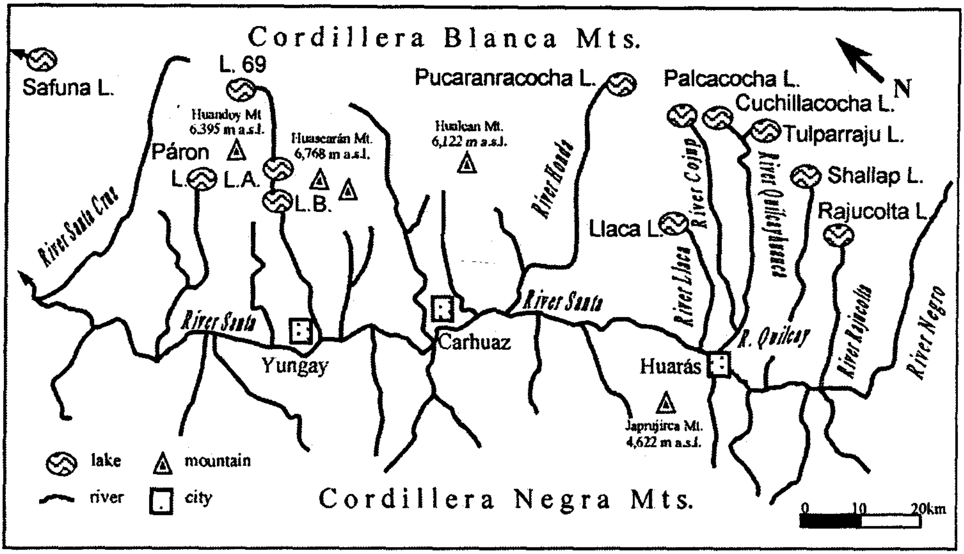

Fig. 1. Location map of the central part of the Calleyon de Huaylas (Santa River Valley) with glacial lakes discussed in the article (L.A. — Llanganco Alto Lake, L.B. — Llanganuco Bajo Lake)

lakes were subject of intense scientific research focused on acquiring information about character and intensity of present geomorphologic processes not just in the Peruvian Andes (Zapata 2002; Rodbell and Seltzer 1999), but also elsewhere (Cenderelli and Wohl 2001; Richardson and Reynolds 2000). In the past, special attention was paid to lakes, which might represent a direct risk for the population settled down stream from them. Many remedial engineering works were performed to mitigate related hazards, e.g. the lowering of water level in the lake Paron by artificial gallery excavated in lateral rock wall (Photo 1).

General description of hazardous processes in the Cordillera Blanca were presented in the past by J. M. Reynolds (1989) or V. Vilímek (1995). The Palcacocha Lake outburst in December 1941 was, together with the 1970 earthquake, most serious catastrophe for the city of Huarás and its inhabitants (Photo 2). Recent studies were oriented on the dam stability of the Palcacocha Lake (Zapata et al. 2003; Vilímek et al., 2005). To evaluate potential hazard for the city of Huarás, imposed by glacial lakes, detailed field studies of two lakes with the largest volume of stored water were conducted during 2003 and 2004.

The main aims of this articles are 1) provide overview of potential hazards associated with deglaciation of glacial lakes drained through Huarás; 2) to study past and recent processes of forming potential hazardous lakes in Cordillera Blanca and finally 3) to asses contemporary vulnerability of Huarás city to potential glacial outburst floods.

Photo 1. Lake Paron dammed by lateral moraine of glacier descending from Huandoy which includes blocks of ice. Its melting is serious danger for loosening strength of the moraine and sudden outburst of the lake is probable. This was the reason for lowering of the lake water (visible on the photo)

Photo 2. The water level in Palcacocha Lake dropped down significantly after the outburst in 1941. The outcomming water destroyed another lake (down in the valley) and large part of the city Huarás (Photo by Z. Patzelt)

Photo 3. Lake sediments of an old lake in the middle part of Cojup valley which dam was broken during the Palcacocha outburst in 1941 (Photo by Z. Patzelt)

Photo 4. Small lakes which evolved in the depressions after the blocks of dead ice melted. Another, larger lake is sitting behind the moraine belonging to glacier descending from Pisco Mt. (Photo by V. Vilímek)

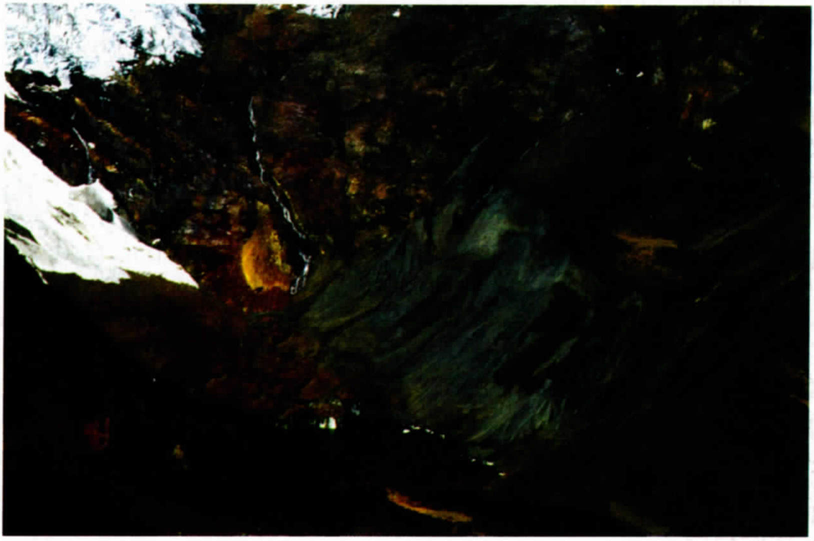

Photo 5. Picture of Lake Tulpacocha taken from the ridge under Pucaranra Mt. (6156 m a.s.l.). Slope movements from unstable slopes are clearly visible (Photo by V. Vilímek)

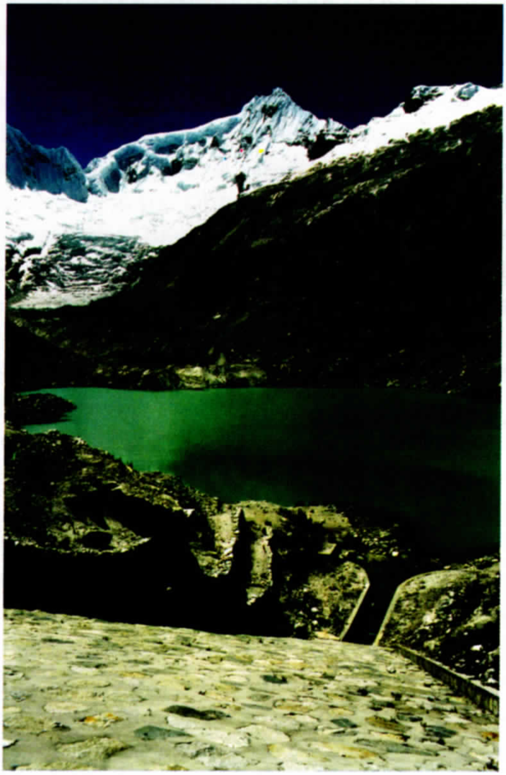

Photo 6. The outlet of the Lake Llaca was reinforced for improving the stability of the moraine dam (Photo by V. Vilímek)

STUDY AREA

Santa River Valley (Calleyon de Huaylas) is at some places rather narrow and more than 200 km long valley, which is bordered by Cordillera Negra in the west and Cordillera Blanca in the east. It drains to the Pacific Ocean. The evolution of the valley has been controlled by tectonic movements and intensive erosion processes (Wise and Noble 2003). General uplift of the Andes (which started in Cretaceous) caused enhanced river channels incision, which mostly followed the preexisting geological structures and tectonic failures (Vilímek 2002).

Cordillera Negra forms east facing slopes of the Santa River Valley, which are intersected with many deep valleys of small streams. Its mountain ridges reach altitudes over 4,000 a.s.l. m with peaks almost 5,000 m a.s.l. high. Majority of the range is composed of volcanic rocks. Cordillera Negra is not glaciated in recent times, but abundant examples of relatively small glacial cirques, U shaped valleys, moraines and lakes are present in this mountain range in elevation above 3,400 m. According to J. F. Coucha (1974) there are only 16 glacial lakes in the Cordillera Negra, which is in great contrast with at least 230 glacial lakes in the Cordillera Blanca.

Cordillera Blanca is rising abruptly from the north-east banks of the Santa River up to the altitude greater than 6,000 m a.s.l. Last glacier advance culminated in Cordillera Blanca between 11,280 and 10,990 ^{14}C yr B.P. and was followed by rapid ice recession, which moved ice front had nearly within its modern limits (Rodbell and Seltzer 2000). The total area of glaciers is according to A. M. Ames (1988) 723 km^2. But due to a significant deglaciation should be the contemporary extent smaller. B. G. Mark (2002) compared the deglaciation in period 1962–1999 with respect to the slope orientation. Glaciers with an eastern aspect showed the highest rate of deglaciation, with a 60% decrease in surface area, and 71% decrease in estimated volume. Southwestern facing glaciers, which are predominant in most glacial valleys in the area under study, showed a 30% and 39% decrease in surface area and volume respectively. The relative difference in the altitude between valley floors and mountain peaks can reach up to 2,000 m and for example, the narrowest part of the Llanganuco valley is just only 500 m wide. In majority of these U-shaped valleys glacial lakes can be found. These lakes are filled mostly by glacial melt water and are dammed by moraines (although some slope processes, as rock avalanches, can play a major role in dam evolution of certain lakes — e.g. Llanganuco lakes). Many of these valleys were formed on fault zones (e.g. Santa Cruz Valley). Thick mantel of fluvioglacial sediments borders west oriented slopes of the Cordillera Blanca and forms undulating, deeply dissected foothills of the mountains. The foothills lie in the altitude between 3,050 m a.s.l. and 3,850 m a.s.l. Width of foothill area vary from 3 km up to 12 km. Highest parts of the mountains are often covered by mountain glaciers.

ORIGIN OF GLACIAL LAKES IN THE CORDILLERA BLANCA

Total number of glacial lakes in the Cordillera Blanca is according to the A. M. Ames (1988) 402, but according to the J. F. Coucha (1974) there exist only 230 glacial lakes. These lakes were formed in cirques in glacially eroded rock basins, often behind moraine dams. Moraine-dammed lakes can be formed by melt water collecting behind moraine or by the coalescence of supraglacial ponds, which was also described in the Himalaya region (Richardson and Reynolds 2000). Some of the lakes in the Cordillera Blanca evolved in the middle or lower parts of the glacial valleys behind recessional moraines. Some of these lakes are nowadays completely filled with sediments (e.g. former lakes in Quilcayhuanca and Rajucolta Valleys), or were emptied by sudden, catastrophic outburst (e.g. former lake in the Cojup Valley — Vilímek et al., 2005, and Photo 3). Moraines often have generally triangular cross sections with the dip of their slopes between 30° and 70° and total high sometimes exceeding 70 m. Other lakes in Cordillera Blanca were formed due to variety of slope processes, which dammed main streams of the valleys. Among these processes belong rockslides, rock avalanches and debris flows, which are in some cases closely connected with deglaciation. E.g. dejection cones can be largely formed by moraine material washed out from glacial sediments of hanging valleys. Typical example of such dammed lake is Llanganuco Bajo located in the glacial valley between Huascaran (6,768 m a.s.l.) and Huandoy Mountains (6,395 m a.s.l., Fig. 1). Rock falls can also contribute to form lake dams. Instability of high and steep rock walls is connected with exfoliation, which follows the deglaciation. Sudden triggering factors are usually seismicity or heavy rains in the rainy period (October–April) or slowly but steady processes of loosening strength due to the physical weathering (Jaboyedoff et al., in print).

CLASSIFICATION OF GLACIAL LAKES ACCORDING TO THEIR DAMS

J. F. Coucha (1974) classified glacial lakes of Cordillera Blanca based on the type of their dam and relation to the glaciers. He characterized each type according to the possibility of producing catastrophic outburst by breaching the lake dam. The classes are as follows:

I. Lakes with direct contact with glaciers;
   1. Lakes with moraine dams filled by melt water or formed from supraglacial ponds;
      a. Dams with steep slopes;
      b. Dams with gentle slopes;
   2. Lakes with bedrock dams;

II. Lakes without direct contact with glaciers;
   1. Lakes with moraine dams;
   2. Lakes with bedrock dams;
   3. Lakes with colluvial dams.

The most dangerous type of dam for producing GLOFs (local name aluviones) is considered to be the type I–1–a (e.g. Palcacocha Lake). It is important to distinguish among moraine-dammed lakes simply filled by melt water or formed from supraglacial ponds, since the later type has dam containing core of stagnant glacier covered by debris (Richardson and Reynolds 2000). The later moraine dam evolution is suggested for ponds on glaciers located above 4,800 m a.s.l. close to the mountain ridges. These glaciers are bordered by extensive moraines lying on steep slopes. If the global warming may influence also these glaciers, rapid forming of very dangerous glacial lakes could be expected. Example of possible consequences of stagnant ice degradation was the 1995 debris flow which occurred between lakes Llanganuco Alto and Bajo and originated below Huandoy Mountain (Zapata 1995).

The most safe glacial lakes are considered those, with base rock dam where only over-spilling may release substantial amount of lake water to the valley. Unfortunately 52% of all glacial lakes in the Cordillera Blanca are dammed by moraine dams and just 40% had dams constitute of base rock and 6.5% are dammed by colluvial material (Coucha 1974). Similar classification was done for the lakes, which drain through streams Llaca and Quillcay to the city of Huarás. Out of 34 identified glacial lakes on the 1984 SPOT image, 21 belong to the most dangerous category, and 13 lakes have dam build mostly by bedrock. The later lakes make only 10% of surface area of all considered glacial lakes whereas 90% of the surface area belong to the moraine dam lakes.

EVALUATION CRITERIA FOR POTENTIAL HAZARD OF GLOFs

Probably most complete summary of all criteria, which are necessary to bear in mind when evaluating potential hazard of GLOFs was published by M. L. Zapata (2002). The following list contains only the most important ones, which have not been mentioned yet: conditions of moraine dams (breached dams, dams with remediation works finished, stagnant glacier ice in dams), width of dam, volume and depth of the lake and hazard of major ice fall, rock fall and debris flow impact to the lake.

Total volume of the lake water is important for evaluation magnitude of potentially dangerous glacial floods produced by glacial lakes. Several well documented cases in the Cordillera Blanca Mountains (e.g. Palcacocha Lake — Vilímek et al., 2005), along with works in Himalayas (Richardson and Reynolds 2000) proved that glacial lake area increase can be as much as 70 m · yr^{-1} in length and 3 m · yr^{-1} in depth. Therefore potential hazard of glacial lake can change remarkably within timescale of years! The evaluation of areal extend of glacial lakes in the central part of Cordillera Blanca Mountains (between River Negro on the east and River Santa Cruz on the west) was done by comparing 1984 SPOT with 1999 LANDSAT satellite images. All together, seven lakes with noticeable increase of areal extend were identified. Two of these lakes (Lake 69 and Tulpacocha Lake; Fig. 1) show evidences of dam breach. Lake surface area increment (m^2) of the lakes as identified from 1984 and 1999 images was calculated as percentage of the original lake surface area identified from 1984 satellite image. Results show that the glacial lakes can expand their area by more than 350% of their initial area within 15 years (e.g. Palcacocha Lake). In contrast, Tulpacocha Lake and Lake 69, have calculated area increment only 50% of their initial areas.

GLOFs from moraine-dammed lakes can be triggered by rock — or ice-fall as well as landslide or debris flow, which can evolve on steep slopes around lake. Therefore stability conditions of all dam slopes as well as glacial cirques should be carefully examined. Impact of ice or debris material to the lake can produce even several tens of meters high tidal waves (in the case of the lake Safuna in 2002, the tidal wave was greater than 75 m — Santillan 2003), which can cause breach of moraine dam and sudden and very rapid discharge of lake water. Such floods may have high damaging effect even more than 85 km down stream and can be recorded on hydrographs located some 200 km away (Richardson and Reynolds 2000).

Field mapping as well as archive photo interpretation proved that glacial tongue retreat along with diminishing of glaciated areas in the glacial circuit play important role in lake slopes stability. The affects of deglaciations are not unambiguous. Case of the Palcacocha Lake, along with some other examples, (e.g. Safuna Lake) show, that glacial tongue retreat may contribute towards activization of debris flow and landslide processes on the inner slopes of the moraine dams. On the other hand, disappearing of glaciers may result in interrupting of slope activity since the glacier melt water are very often the driving force for dangerous slope processes (e.g. debris flows, landslides).

GLOF HAZARD EVALUATION FOR THE CITY OF HUARÁS

Moraine dam conditions of selected lakes and results of detailed field studies of selected lakes north of Huarás are summarized in Table 1. According to these data, three lakes produced GLOFs: Rajucolta lake in 1883 and Palcacocha lake in 1941 and lake Tulpacocha produced two floods within 5 years during 1950'. The Palcacocha flood killed 4,000 inhabitants of Huarás and destroyed about 970,000 m^2 of the city along the River Quillcay. Total estimated volume of this flood was between 9,000,000 m^3 and 11,000,000 m^3 of water (Vilímek et al., 2005). In all other cases only the infrastructure was damaged. Due to these events, hazard of producing new devastating GLOFs is fairly low, even though, the most recent works show that Palcacocha and Tulpacocha lakes increased remarkably in their volume. On the other hand vulnerability of the city of Huarás increased dramatically since last recorded GLOF. The higher vulnerability is connected with fast development of the city. Whereas in the 70's the population of Huarás was around 30,000, now is estimated up to 90,000 people. Also the urban area increased and new houses are be-

Table 1

Characteristics of selected lakes north of Huarás (based on glacier and lake inventory done by INRENA, Peru)

Lake	Area [m²]	Volume [m³]	Depth [m]	Moraine dam conditions	Date of dam outburst	% of lake basin covered by glacier	Direct contact of glacier with lake ▲	Hazard of ice block/landslide impact ▲
Llaca	43,988*	274,305*	16.8*	reinforced	no	66	yes	no/low
Palcacocha	342,332**	3,960,000**	15**	breached, reinforced	13.12.1941	76 ▪	yes	low/high
Tulparraju	150,760*	1,620,000*	17*	breached, reinforced	1953	74	yes	low/low
Cuchillacocha	141,000*	2,230,000*	28*	reinforced	?	63	no	medium/low
Shallap	165,251**	3,467,585**	36.6**	reinforced	?	63	no	no/low
Rajucolta	512,723**	17,546,151**	73**	breached, natural	24.06.1863	68	yes	medium / medium

▲ Based on N. L. Diaz (1993) and field investigation 2003, 2004
* According to original bathymetry from 1970
**According to 2004 bathymetry
▪ Based on 1970 aerial picture interpretation

ing constructed not only within the limits of 1941 devastating GLOF, but even directly on the temporary dry parts of the Santa River bed. Huarás is also one of the most important touristic centers in Peru.

Based on interpretation of the 1984 SPOT satellite image another 14 glacial lakes in Cordillera Blanca were identified, which may experienced outbursts in the past. Among these only 5 events were dated (Zapata 2002) and 4 other appear fresh enough that it may be concluded that the dam breach happened within last 150 years.

All information mentioned above can be concluded, that the potential hazard of GLOFs originating from glacial lakes drained through Huarás is fairly low. Despite of that, ongoing thoughtful monitoring and maintaining or reinforced lake dams is necessary to ensure safety of the growing city.

CONCLUSION

Evaluating all criteria for potential hazard of glacial lakes with possible impact on the regional capital Huarás clearly show, that the overall hazard is rather low. Despite of that it is very important to continue monitoring of the lakes dam stability conditions and the effects of the rapid deglaciation (Mark 2002; Vilímek et al., 2005) also because of continuing increase of vulnerability of the Huarás city. The most dangerous glacier lake type is moraine-dammed lake with narrow, steep dam containing stagnant glacier ice (Photo 1).

As show the recent works, surface area and volume of glacial lakes increased drastically within last two decades. For example, the increase of the Palcacocha lake volume between 1972 and 2004 was more than 3,400,000 m^3. This comparison is based on bathymetric measurements done by N. Ojeda (1974) and M. L. Zapata et al. (2004). Comparison of 1984 SPOT and 1999 LANDSAT satellite images proved that it is possible to expect substantial increase in volumes of other lakes because of their large surface area enlargement, e.g. Tulpacocha (river basin Cojup), Pacllashcocha (river basin Honda). Relative numbers, which can be used to compare lake area expansion with its original area, were calculated for these lakes. Those, rather large changes in lakes surface areas and stored water volumes are caused by ongoing climate warming and subsequent glaciers melting. Almost all the lakes (apart from one) with substantial surface area increment identified on the 1984 and 1999 satellite images are dammed by moraines and at least three of them produced GLOFs in the past. This shows importance of permanent monitoring of natural hazards connected with glacial lakes.

Important is also finding that the affects of deglaciations are not unambiguous. Field mapping clearly showed that activity of often dangerous slope processes depends largely on supply of glacier melt water. The availability of glacier melt water on specific slope or its part depends on temporal progress in deglaciation.

Many works along with direct measurements on the Corrdillera Blanca fault (Montarion 2001; Vilímek and Zapata 1998; Wise and Noble 2003) prove ongoing tectonic activity of the region. It is not possible to exclude major earthquake in near future, which may substantially change natural hazards distribution within the region.

ACKNOWLEDGEMENTS

This work was supported by the project MSM 0021620831 from the Czech Ministry of Education, Youth and Physical Culture.

Special thanks belong to the INRENA office in Huarás (former Electroperu) for their essential data and organizing support.

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STRESZCZENIE

V. Vilímek, J. Klimeš, M. Zapata

POWODZIE WYWOŁANE GWAŁTOWNYM SPŁYNIĘCIEM JEZIOR LODOWCOWYCH W OBSZARZE HUARÁS, CORDILLERA BLANCA, PERU

Historyczne źródła dokumentujące powodzie wywołane gwałtownym spływem jezior okołolodowcowych pokazują wielkie niszczycielskie oddziaływanie na wysokogórskie środowisko wielu obszarów w górach Cordillera Blanca w Peru. Obrazy skutków tych zdarzeń uzyskane z satelitów SPOT i LANDSAT zastosowano w studiach katastrofalnych zjawisk przyrodniczych w kontekście współczesnego ocieplenia klimatu. Dane uzyskane z obrazów satelitarnych uzupełniono pomiarami naziemnymi. Stwierdzono, że w ostatnich dwóch dekadach drastycznie zwiększyło się zagrożenie dla meszkańców miasta Huarás. Nastąpiło znaczne powiększenie powierzchni i kubatury jezior. Są to jeziora zaporowe, zamknięte systemami moren. Powtarzane kartowanie terenowe pokazuje, że aktywność procesów stokowych jest zwiększona wskutek zasilania pokryw przez wody topniejących lodowców. Ponadto ryzyko wystąpienia powodzi jest zwiększone przez współczesną aktywność tektoniczną tego obszaru.