

Influence of glacial retreat on natural hazards of the Palcacocha Lake area, Peru

Abstract In this article we describe natural hazards associated with outburst floods of Palcacocha Lake and landslide events on the slopes of its moraine dam, in Cojup Valley, Cordillera Blanca (Peru). These events occurred in the last 70 years and some of them resulted in disasters, which strongly affected the city of Huarás. Field investigations and reference expression hydrodynamic tests as well as archive satellite images and aerial pictures were used to describe the evolution of hazards connected with Palcacocha Lake. Expression hydrodynamic tests proved a high permeability of sandy gravels glacial sediments, which form the present-day lake dam. Seepage through the natural dam forming small ponds below the overflow spillways occurs. A retreat of the glacial tongue causing an increase of the lake volume and unloading of the slope toe areas are the most important recent processes that influence the potential hazards affecting the Cojup valley. The research has proved that the climate warming and ongoing deglaciation play a very significant role in the change of natural hazards conditions in high mountains.

Keywords Glacial lake · Outburst floods · Moraine dam · Cordillera Blanca · Peru

Introduction

The glacial Palcacocha Lake is located on the western slopes of Cordillera Blanca in the uppermost part of the Cojup valley, which is drained by Cojup stream into the Rio Quilcay draining itself into the Santa River (Calleyon de Huaylas), Ancash region (Fig. 1). Two ice and snow-capped mountains close the valley just above the lake—Nevado Palcaraju (6,264 m a.s.l.) and Nevado Pucaranra (6,156 m a.s.l.). Since the rupture of the Palcacocha Lake on December 13, 1941, which caused a disastrous outburst flood (local name “aluvion”) and claimed 4,000 lives in Ancash capital of Huarás (Electroperu 1984), there is a strong concern of natural dams’ stability in this part of the Andes.

Various catastrophic events are initiated within the glacier foreland, defined by the limits of the Little Ice Age advance (Evans and Clague 1994). The landslide activity in the recently deglaciated areas is one example. Nevertheless, impacts of catastrophic events may be felt far beyond the glacier foreland limits. Especially outburst floods and high mobile debris flows represent a significant threat to human settlements and economic infrastructure.

The history of documented natural hazards in the Ancash department is going back to the year 1702 (e.g. Reynolds 1992; Vilímek 1995; Zapata 2002). Evidence of similar catastrophic events was also examined during field investigations on the moraine dam of Rajucolta Lake (basin Rajucolta, dam rupture in 1883, Zapata 2002). Evans and Clague (1994) described outburst floods that had occurred mainly in British Columbia and Cordillera Blanca; Richardson and Reynolds (2000) those in Himalayas while Hermanns et al. (2004) those in Argentina.

The outburst flood of the Palcacocha Lake destroyed the moraine dam of the Jircacocha Lake, the waters of which significantly contributed to the devastation of Huarás. The city of Huarás is located in the Calleyon de Huaylas (the Santa River Valley), only 23 km downstream from the Palcacocha Lake and 15 km from the Jircacocha Lake. The water surface of the Palcacocha Lake has varied significantly in the last decades (after the 1941 outburst it sank approximately by 47 m) and now it is at 4,563 m a.s.l (Zapata et al. 2004).

On March 19, 2003, a landslide slipped down from the inner part of the left lateral moraine into the Palcacocha Lake and caused minor flooding in the Cojup valley. Without any relation to this event, NASA informed (Steitz and Buis 2003) on April 8, 2003, based on the ASTER satellite image interpretation, about a potential glacial disaster threatening the city of Huarás (Fig. 1), resulting from a crack in the glacier above the Palcacocha Lake.

The 2003 events along with evidence of ongoing climate warming (e.g. Kaser 1999; Rodbell and Seltzer 2000; Kaser et al. 2003; Fig. 2) showed the need for new moraine dam stability investigations of the Palcacocha Lake. The main task was to evaluate whether a potential outburst flood would be able to reach the destruction intensity of the 1941 event with respect to the increasing population density of the formerly affected areas.

Methodology

Time series of ground-based as well as airborne images were analysed to study glacial retreat in the mountains surrounding of Palcacocha Lake and related surface processes and conditions. This helps to describe the landscape evolution of the area. We used air photos from 1962 and 1970 (Fig. 3), a 1984 SPOT image, and LANDSAT images from July 1999 and March 2003 LANDSAT as well as ground photos of the Palcacocha Lake: the 1932 ones by H. Kinzl (Fig. 4), the 1974 ones by N. Ojeda and recent pictures from 2003 and 2004 (e.g. Fig. 5).

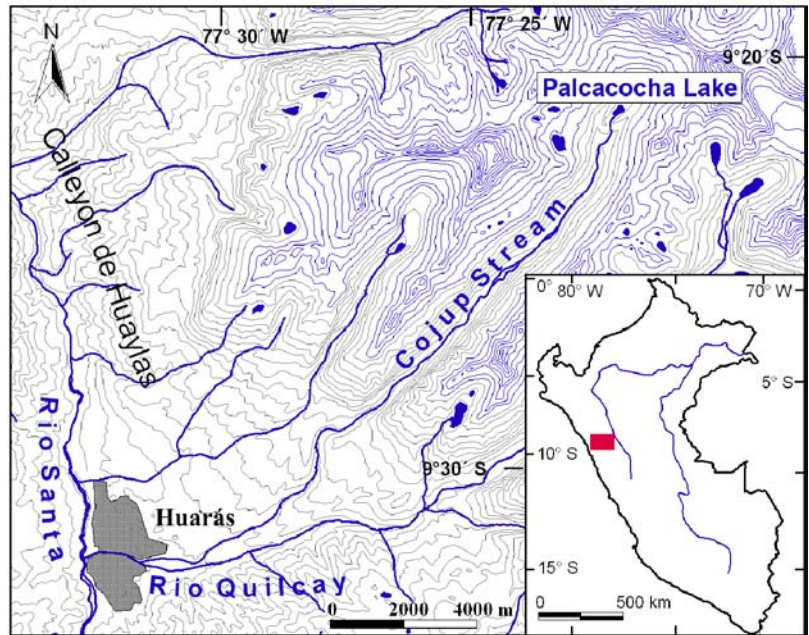
Field studies and field mapping were carried out in July 2003 and September 2004. We mapped and analysed landscape features (such as recessional moraines, depleted glacial lake basins, related deposits and the recent geomorphologic processes in the entire Cojup River valley with special attention to the Palcacocha Lake moraine dam (e.g. measurements of the dip of the moraine slopes).

Furthermore, a hydrogeologic field survey was carried out in September 2004 during which surface recharge and hydraulic properties of superficial deposits were verified by 16 reference expression hydrodynamic tests (Fig. 3, grouped into 5 sites). The time necessary for infiltration of 500 ml of water in a circle area of 110 mm in diameter was measured.

Global climate change and glacial retreat

Thompson et al. (1995) described climatic conditions in the area of Cordillera Blanca on the basis of two ice cores drilled at Huascarán

Fig. 1 Location map of Huarás and the Palcacocha Lake (topography by IGN, Peru)



Mt. These data extended back to the Late Glacial Stage (LGS) approximately 20 000 years BP. Since that time other studies were concluded and Thompson et al. (2000) pointed that LGS conditions in the Andes were much cooler than during the Holocene—perhaps by as much as 8°C.

Stratigraphy and radiocarbon data from the western side of the Cordillera Blanca clarify the timing of the major glacier readvance during the late glacial. It reached the maximal position around 11 000¹⁴C yr. B.P. After that culmination, a rapid glacial retreat occurred probably due to an increased aridity (Rodbell and Seltzer 2000).

Fig. 2 Monthly average temperatures recalculated for the Cordillera Blanca Mountains for altitude of 6000 m a.s.l. with linear trend line in red (modified after B. Pouyaud, IRD, France, from archive of N. Santillán)

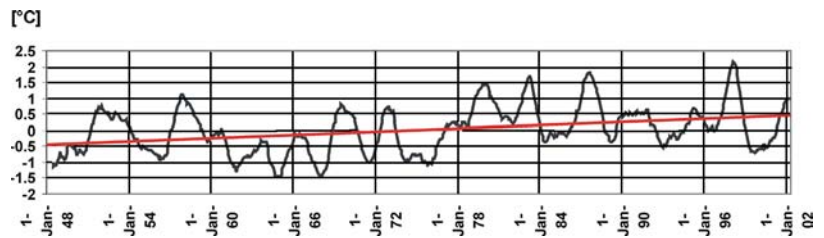


Fig. 3 Glacial retreat history between 1970 and 2003 based on the results of the satellite images and 1970 aerial photo interpretation of the Palcacocha Lake vicinity

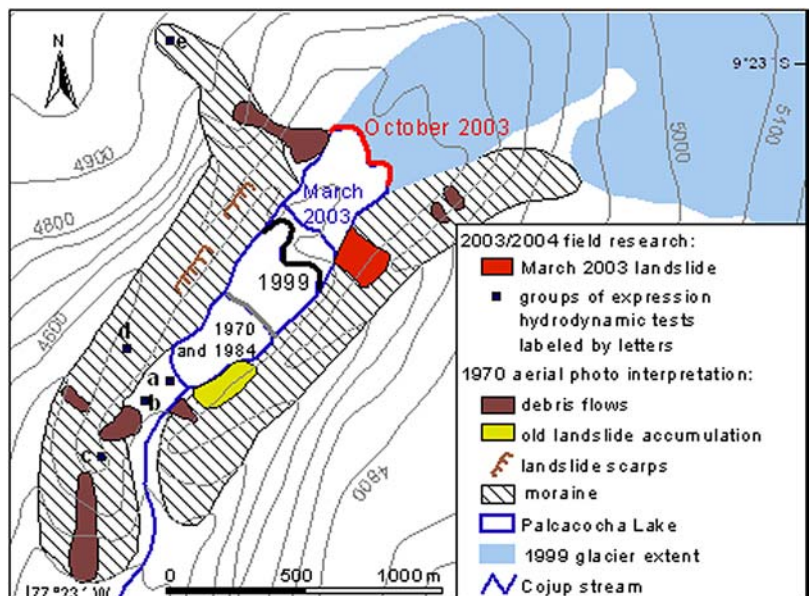


Fig. 4 Palcacocha Lake in 1932 (photo by H. Kinzl)



Fig. 5 Front view of the Palcacocha Lake in September 2004 showing the two artificial concrete dams (photo by Z. Patzelt 2004)



Thompson et al. (2000) mentioned that temperatures during the Holocene were the coolest in the most recent Neoglacial—the Little Ice Age. On the contrary during the last 200 years, the temperature has markedly increased and the twentieth century has been the warmest in the last 6000 years.

According to Hansen et al. (1999), the globally averaged temperature has increased by 0.7°C since the end of 19th century. In larger detail there was a period of warming in the last century on a global scale (1880–1940), followed by cooling (1940–1965) and again warming (1965–1985), (Hansen and Lebedeff 1987). However large variations were observed on a regional scale; e.g. the Peruvian Andes experienced a temperature increase of $3\text{--}5^{\circ}\text{C}$ between 1880 and 1940 (Evans and Clague 1994). Following the significant ice losses in the

1920's and 1930's, five glacial moraine dams ruptured in Cordillera Blanca: Solteracocha Lake (1932), Artesa Lake (1938), Magistral Lake (1938), Palcacocha together with Jircacocha Lake (1941), Ayhuinyaraju together with Carhuacocha Lake (1945), and Suerococha Lake (1941) in adjacent Cordillera Huayhuash. An additional strong mass loss occurred during the 1950's and 1960's (Kaser et al. 2003)—two moraine dams were broken in Cordillera Blanca in that period: Jancarurish Lake (1950) and Millauacocha Lake (1952).

However, glacial volume does not depend on temperature alone. Also precipitation influences glacial ice balance significantly. For example during warming period (1965–1985) there was a minor glacier advance (1974–1979) due to relatively high annual precipitation rates (Kaser et al. 1989). According to Kaser (1999), a reduction

of air humidity, with all the consequent changes in energy and mass balance, is suggested to be the major reason for the retreat of tropical glaciers since the end of the Little Ice Age. The rise in air temperature explains only a part of the recession.

The glacial retreat calculated from 18 mountain ranges in Peru was 21.9% during the 1970–1997 period; shown by a drop from 2,042 to 1,597 km² of the surface area of glacial ice. The decrease of glacially covered surfaces in the Cordillera Blanca was 15.5%; with a decrease from 723 km² to 611 km² (Ames et al. 1988). Mean ablation rates at the lowest parts of the glacier tongues are markedly higher during the wet season than during the dry season (Kaser et al. 1989).

Mark (2002) distinguished glaciers in Cordillera Blanca according to their slope orientation. Glaciers with an eastern aspect showed the highest rate of deglaciation, with a decrease of 60% surface area, and 71% in estimated volume from 1962–1999. Southwestern aspect glaciers, which are there more common, showed a 30% and a 39% decrease in surface area and volume respectively. This fact could be explained, according to Kaser and Georges (1977) in Mark (2002), by the existence of late afternoon clouds which obstruct the western facing glaciers from the direct solar irradiation.

Geomorphological and geological settings

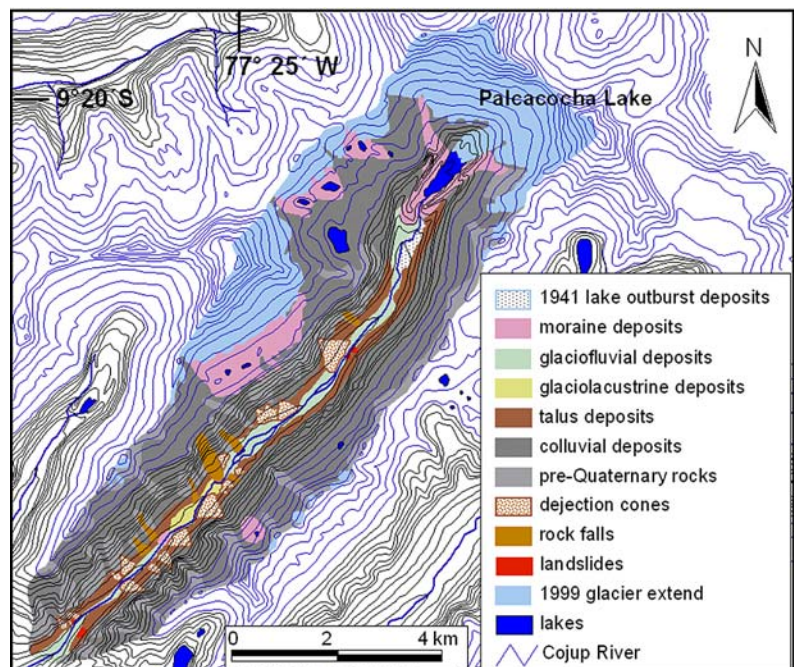
The Cojup valley comprises various types of intrusive rocks, such as granites and granodiorites (Morales 1967). The main ground water collector is the sedimentary fill of the glacial valley. It is assumed that some water infiltration occurs through the fissure systems in the massif rocks. Groundwater is recharged both by precipitations and by melt water from thawing ice in the glacial foreland. The Cojup valley is a typical glacial valley with very strong recent fluvial remodelling. The inclination of its slopes varies between 30° and 40° in their lower part where they are covered by talus deposits, which modify the typical glacial U shaped profile. The free rock faces above the talus deposits dip usually between 60° and 80° and supply the valley bottom with

huge boulders (up to 5 m in diameter). Nevertheless, some of them could be transported by the outburst flood. Richardson and Reynolds (2000) described a huge block of estimated 200 tones transported by glacial lake outburst flood from Chubung Lake (Rolwaling Himalayas, Nepal) deposited on the surface of a debris fan. Slopes between the ridge tops and free rock faces are generally gentler (25°–15°) covered with angular boulders resulting from frost shattering eventually with moraine accumulations (Fig. 6).

Even though accumulation forms dominate the valley, strong erosion of the Cojup stream is apparent especially in the lowest part of the watercourse in the foothills of the Cordillera Blanca Mountains. The stream forms a deeply incised ravine like valley in the thick mantle of glaciofluvial sediments with abundant landslides on its banks. This situation is comparable with the neighbouring valleys. The neotectonic uplift of Cordillera Blanca enhanced the erosion activity in uplifted areas (Vilimek and Zapata 1998). However, the Cojup stream has eroded up to 50 m deeper than the adjacent streams to the SE and NW. This fluvial remodelling was caused by the disastrous outburst flood in the year 1941.

The morphologically most distinct features of the valley bottom are recessional moraines (Fig. 6). The youngest moraine of the recent age has formed the natural dam of the Palcacocha Lake (before its failure in 1941). According to its position and fresh appearance it might be a moraine deposited during the Little Ice Age glacial advance. Another older recessional moraine retained the Jircacocha Lake, which was formed 8.3 km downstream from the Palcacocha Lake. This natural dam was destroyed during the 1941 outburst flood event. No dating of any of these moraines has been done up to now, therefore the paleoglacial history of the Cojup valley can be only roughly estimated based on correlation with the detailed radiocarbon data published by Rodbell and Seltzer (1999). Their work focused on Breque Lake (3975 m a.s.l.), which is situated approximately 30 km SE from the Palcacocha Lake in the River Negro drainage basin. They pointed out that during the last glacial maximum glaciers extended down the valley to an altitude of ~3800 m a.s.l. and the most extensive

Fig. 6 Holocene deposits of the Cojup valley



Holocene ice advance reached ~4300 m a.s.l. Current ice fronts are generally at 5000 m a.s.l. or higher.

The extent of the Jircacocha Lake is marked by a natural dam formed by the recessional moraine and by the upstream extent of fine-grained sediments at the former inlet. The natural moraine dam is cut by an 80 m deep channel in the glacial sediments, which is just 10 m wide at its bottom and 200 m wide at the top of the moraine dam. The glacial sediments of this moraine dam are overlaid at both sides by talus deposits from the adjacent steep slopes. Upstream the failed moraine dam, there is a flat lake basin filled with well sorted, layered, fine grained lacustrine and proluvial sediments in which the Cojup stream carved 15 m deep channel. Only about 5 cm of soil developed on the top of the lacustrine sediments. The initial water level of the depleted lake is clearly marked by a difference in the type and age of vegetation at the slopes and by remnants of well-sorted and fine-grained sediments on the inner slope of the dam indicating a maximum depth of 30 m.

Glacial lakes classifications

The basic classification of glacial lakes in the Cordillera Blanca Mountains was published by Coucha (1974). He divided the lakes into two major groups according to their relation to the glacier tongue. In the first group, there are lakes where the glacier is directly connected with the water body and in the second group those, which lost a direct contact with the glacier snout. Both groups are further subdivided according to the material forming the dam into lakes with moraine, bedrock or colluvial dams. According to this classification, 52% of all glacial lakes in Cordillera Blanca belong to the first group dammed by moraine dams. Also the Palcacocha is a moraine-dammed lake and the glacier descending from Nevado Pucaranra is even today directly connected to its water body. Possible mechanisms of moraine dam failures were classified e.g. by Reynolds (1992): (a) melting ice core; (b) displacement wave from rock/ice avalanche into a dammed lake; (c) settlement and/or piping within a moraine dam (resulting from seismic activity); (d) catastrophic sub-glacial drainage. Examples of all of these failure mechanisms can be found in the Cordillera Blanca Mountains.

Hydrogeological conditions

An important result of field investigations from 2004 is identification of lake water seepage through the present lake dam. Suggested seepage water flows from the lake through the dam and basal moraine sediments where it forms two small ponds (for location compare with site b of the expression hydrodynamic tests in Fig. 3). The surface of the Palcacocha Lake water level is 8 m above the water level of these ponds. Headsprings of seepage water with a yield of litres per second were estimated on the pond's floors. The location of the ponds along with the observed inflow on their floors favours their seepage origin over pond's formation due to stagnant ice blocks. Lateral water leakages at a rate of 1.10^{-1} l/s were found on slopes of the original lake dam burst in 1941. On the surface of the current dam, body depressions of up to 10 m in diameter formed presumably by a subsidence in places of an intensive sub-surface water flow.

The results of the reference expression hydrodynamic tests (see Table 1) indicate a high to very high permeability of the superficial deposits in the ascertain range of coefficients of permeability $k=1.10^{-2}$ up to 1.10^{-5} m/s. They also show clearly that the highest permeability is found in sandy gravel sediments, which form the present dam below the overflow spillways in areas where headsprings of seepage water form the ponds. This area is covered by the youngest

Table 1 Results of the reference expression hydrodynamic tests, each group of test sites is located on the Fig. 3

Test No	Time (s)	Sediment texture	Group of test sites
1	86	Clayey sand	a
2	21	Fine sand	
3	33	Fine sand	
4	13	Sandy stony gravel	
5	74	Sandy stony gravel	b
6	33	Fine sand	
7	28	Fine sand	
8	15	Sandy gravel	
9	22	Sandy gravel	
10	4	Poor sandy gravel	
11	6	Poor sandy gravel	
12	116	Sandy loamy gravel	
13	193	Sandy loamy gravel	c
14	56	Sandy loamy gravel	
15	63	Sandy loamy gravel	d
16	151	Loamy sand	e

sediments formed by the over spilling of the dam on March 19, 2003. The increasing portion of loamy components is accompanied by a decreasing permeability and an increasing stability of sediments. Vegetation cover induces a significant stabilization of outer slopes of the moraine.

Glacial tongue retreat and volume changes of the Palcacocha Lake

There are many glacial lakes in the Cordillera Blanca Mountains with a well-documented glacial tongue retreat history (e.g. Kaser et al. 1996; Thompson et al. 2000). Unfortunately, no detailed monitoring information is available for the Palcacocha Lake. Therefore, its glacial history was described with the help of aerial photographs and satellite images. Only a rough estimate about glacier terminus position based on the H. Kinzl photo's (Fig. 4) can be made for the time prior 1941. We concluded that the glacier tongue was either in the similar position as mapped by the 1970 aerial photo or few tens of meters closer to the glacier amphitheatre. On other hand, the position of the glacial terminus on the 1970 aerial photo (Fig. 7) can be very well identified. The maximal length of the lake was 405 m at that time. Just a very little (if any) change can be detected by comparison of the 1970 aerial photo with the 1984 SPOT satellite image. It means that the glacier terminus retreated only by several meters or remained on the same position as in 1970. The irregular yellowish spot at the tip of the glacier terminus shown on the July 1999 LANDSAT image was interpreted as almost debris-free ice or snow floating on the lake disconnected from the glacier tongue itself. Based on the field observations from 2003 we assume that these loosen floated ice blocks melted during the year 1999. Therefore, the final glacier retreat between 1984 and 1999 was up to 340 m within 15 years. Similar scenario is suggested for the year 2003. The large part of the glaciated area shown on the March 2003 SPOT image consisted of broken floating ice blocks, which melted within the next 7 months. This was proved by March and October field investigations. The bathymetric measurements from October 2003 proved a total glacier retreat of 530 m between 1999 and 2003. The presented data show a total retreat of the Palcacocha Lake glacier tongue of about 760 m from 1970 to October 2003 (within 33 years)!

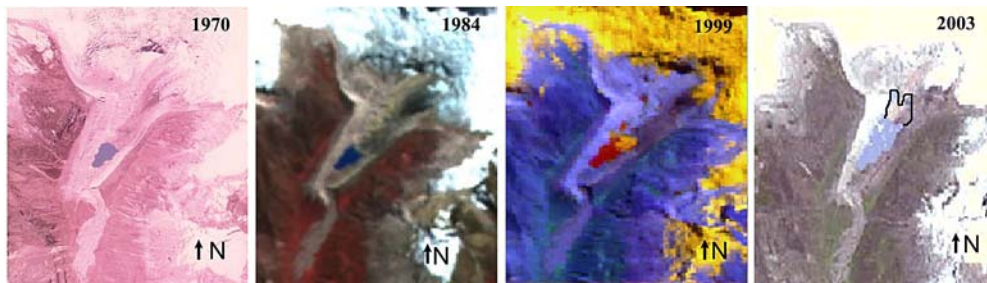


Fig. 7 Glacial tongue retreat as can be seen on the 1970 aerial photo, 1984 SPOT, July 1999 LANDSAT and March 2003 LANDSAT satellite images. Yellow color displayed on the July 1999 LANDSAT image indicates debris-free ice or snow. Black line on the March 2003 SPOT image displays glacier retreat identified during the bathymetric measurements in October 2003

Based on the picture by H. Kinzl from 1932 (Fig. 4), it can be estimated that the Palcacocha Lake had filled up to 4610 m a.s.l. prior 1941. This lake water level was 47 m higher than the present one of 4,563 m a.s.l. (Zapata et al. 2004). The estimated volume of the Palcacocha Lake before its rupture on December 13, 1941 based on the topographic maps was between 9,000,000 and 11,000,000 m³. The water filled up the lower lake (Jircacocha) in the Cojup valley causing failure of its moraine dam and following outburst. The lower lake was completely emptied and contributed by its volume of approximately 4,800,000 m³ to the flood, which reached the City of Huarás killing about 4,000 inhabitants (Electroperu 1984) and destroying about 970,000 m² of the city along the Quilcay River.

After the 1941 event, the water level dropped down and nowadays it is retained behind an 8 m high basal moraine dam. This natural dam was reinforced with two concrete overflow spillways built in its lowest portions during 1972–1974. The left (south) overflow spillway has a 33 m long evacuation channel, which controls the water level in the lake (Fig. 5). These preventive measures lowered the water level by 1 m (Ojeda 1974) resulting in a volume of 514,800 m³ and an area of 62,600 m². Glacial retreat which occurred mainly during the last 21 years (with a strong acceleration between 1999 and 2003) caused an increase of the lake volume 7.7 times to 3,690,000 m³ while the lake area increased 5.5 times to 342,332 m² (Zapata et al. 2004). Its maximal depth increased from 13 m up to 14.9 m, but the water level remained at the same elevation as in 1972. The increase of the depth is due to the fact, that the lake was enlarged in the area where the natural basin is deeper (this area was up to now filled with glacier).

Recent landslide activity on the Palcacocha Lake moraine dam slopes

On March 19, 2003, a planar landslide of unconsolidated material of the inner moraine fell into the lake water and hit a part of the glacial tongue (see Fig. 8). The main triggering factor of the landslide was extensive rainfall precipitation which over-saturated the moraine material. No evidence about permafrost involvement has been found. Rough volume estimate of the landslide is between 50,000 and 75,000 m³. This high uncertainty is due to only a proximate knowledge of the pre-landslide slope topography and to the fact that almost the entire landslide accumulation lies on the lake floor. The impact of the material produced a tidal wave more than 8 m high, which overflowed the natural and artificial parts of the lake dam and caused a minor flood in the Cojup stream and the Quilcay River. The sediments carried by the flood blocked the water treatment plant of Huarás.

Discussion

Glaciation processes of the Palcacocha Lake area earned a broad public attention thanks to the NASA news release (Steitz and Buis 2003) from April 8, 2003. NASA informed, basing upon a quick interpretation of ASTER satellite images, about a large crack in the glaciers bellow Palcaraju and Pucaranra peaks, which might have been highly dangerous for the inhabitants of the Huarás City. The field investigations from March and June 2003 did not prove the existence of any large crack in the glaciers, which would be able to produce a collapse of a huge ice block to the lake. Misinterpretation of the ASTER satellite image was probably reasoned in two distinct linear features, which are in fact only boundaries of different morphological units of the glacial amphitheatre. The upper one runs along the toe of steep rock faces bellow the Palcaraju and Pucaranra Peaks and the lower one marks a zone of séracs, which corresponds to a drop-off in the profile of the slope (Fig. 5). The séracs zone is largely broken, but no single prominent crack was identified there—just only a large number of smaller séracs which could fall into the lake but not all at once.

The causes and mechanism of the 1941 rupture of the Palcacocha Lake are not exactly known but an earthquake can be excluded because no seismic activity was recorded there before the disaster. Also no evidence proving presence of stagnant ice inside the moraine was found within the Palcacocha Lake area. Even though there are no precipitation records available for the time of rupture, we can with a high probability attribute the dam failure to heavy rains, because it happened during the rainy season. Over-saturation of the moraine material coupled by intensified water erosion of the lake discharge canal could have led to the dam failure. This assumption is supported by the already advanced erosion of the upper part of the dam as it can be seen on the 1932 picture (Fig. 4). Therefore, it seems that the mechanism of the Palcacocha Lake dam failure could be regarded as a new unique class, which is not included in the classification published by Reynolds (1992). It also implies that the moraine dam may fail regardless the relation of the glacial lake and the glacier tongue as is suggested by classification of Coucha (1974). The effect of a displacement wave from rock fall, icefall and/or landslide could also contribute to the dam bursting, but no evidence was found to support this possibility. Nevertheless, several potentially dangerous ice blocks were identified high on the steep rock walls of the Palcaraju and Pucaranra Mountains (Fig. 9). The possible fall of these blocks into the lake could probably cause a sudden and large outburst of the lake water due to their volume and kinetic energy resulting from their high position on the rock wall.

Fieldwork as well as interpretation of the 1970 aerial photo showed difference in landslides and debris flows occurrence frequencies

Fig. 8 NE view of the March 19, 2003 landslide area indicated by the narrow black line (photo by J. Klimes, July 2003)



between the inner and the outer slopes of the Palcacocha Lake moraine dam (see Fig. 8). The 1970 aerial photo interpretation revealed two debris flows on the outer slopes and five debris flows along with two landslides (indicated only by scarps) on the inner slopes. The time of the origin of these debris flows and landslides is unknown. Since 1970, no new debris flows have occurred on the outer slopes in contrast to the inner slopes where one large planar landslide occurred in March

2003 (NW slope). The apparent differences in stability conditions between the inner and the outer slopes are mainly due to different slope inclinations as were measured by compass in the field. The outer slopes dip in their upper parts between 27° and 34° , and in their lower parts $\sim 18^\circ$. Whilst the inclination of the inner slopes is 72° in their upper parts declining to 45° in the toe areas covered by accumulation. Older surface and more vegetation cover also indicate more



Fig. 9 Potentially dangerous ice block bellow the Nevado Palcaraju (6,264 m a.s.l) in the starting zone of snow avalanches. Vertical height shown is about 200 m (J. Klimes, July 2003)

stable conditions of the outer slopes. Glacial tongue retreat from the Palcacocha Lake leads to an unloading of slope toe areas which facilitates mass wasting processes. These processes smooth profiles and stabilize the slope, accumulate the slope material on the lake floor and widen the lake. The slope decrease has been detected by a comparison of the 1974 photographs of the Palcacocha Lake (Ojeda 1974) and the recent pictures (e.g. Fig. 5). The 1974 picture also shows a large amount of moraine material on the NE slopes which was supported by the glacial tongue. All this material is missing on the 2004 picture (Fig. 5), a large landslide occurred there in March 2003 and the lake has been also widened in that part. The change of the lake shape is visible on Fig. 7. These data suggest that the spatial distribution of the recent landslides on the inner moraine slopes may be partly governed by the glacial tongue position and temporal occurrence depends on precipitation intensity.

Conclusion

The overall hazard connected with Palcacocha Lake remarkably dropped after the disastrous flood in 1941. This event has reduced the volume of the lake from approximately 9,000,000–11,000,000 m³ to 514,800 m³ in 1972. The flooding of Huarás City was so much disastrous also because of a significant contribution of the estimated volume of around 4,800,000 m³ from the Jircacocha Lake which was destroyed during the flood. Our recent investigations show that due to the rapid deglaciation, the volume of Palcacocha Lake raised from 514,800 m³ in 1972 up to the actual 3,690,000 m³ (2003). Most of the changes in the Palcacocha Lake glaciation occurred during the last 21 years (with a strong acceleration between 1999 and 2003). The area of the lake increased from 62,600 m² (1974) up to 342,332 m² (2003). The volume will further gradually increase, if the glacial tongue continues to retreat. Despite of that, the volume of a potential flood from the lake is nowadays 4 times smaller than it was during the 1941 outburst flood.

Hydrogeological investigations showed that seepages through the contemporary dam body, especially beneath the side overflow spillway, document lack of homogeneity of the ground moraine lake dam and indicate places of potential instability. Formation of terrain depressions on the surface of the dam may document suffusion of fine particles from the dam body and thus its destabilization. The technical construction of the lake outflow prevents water level oscillation and bank erosion is therefore minimised. However, it is very important to maintain the contemporary artificially reinforced natural dam as well as the outflow channel of the Palcacocha Lake in good conditions to minimize the probability of dam outburst. It is also desirable to periodically monitor the intensity of leakage through the dam body to know whether the situation is not worsening. Recharge of precipitations is highly variable in dependence on the seasonal and long-term oscillation of rainfall intensity.

Currently, the highest danger imposed on the Huarás population is represented by landslides falling from the inner moraine slopes of the Palcacocha Lake causing displacement waves and overtopping of the dam, which is causing erosion of the dam and subsequent floods in the Cojup valley. This danger has increased due to the rapid glacial tongue retreat. We think that the glacial tongue played an important role in the inner slope stability as it was stabilizing the toe area of the slopes. Potentially dangerous ice blocks were identified high on the steep rock walls of Palcaraju and Pucaranra Mountains. A fall of these blocks to the Palcacocha Lake could probably cause a sudden and very large outburst of lake water, probably even larger than the 2003 one.

Nevertheless, a single overspill of the dam crest after a landslide or an avalanche cannot reach the intensity of the 1941 outburst flood, because of a much lower lake volume.

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