

Impact of a rock avalanche on a moraine-dammed proglacial lake: Laguna Safuna Alta, Cordillera Blanca, Peru

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Abstract

Moraines that dam proglacial lakes pose an increasing hazard to communities in the Andes and other mountain ranges. The moraines are prone to failure through collapse, overtopping by lake waters or the effect of displacement waves resulting from ice and rock avalanches. Resulting floods have led to the loss of thousands of lives in the Cordillera Blanca mountains of Peru alone in the last 100 years. On 22 April 2002 a rock avalanche occurred immediately to the south-west of Laguna Safuna Alta, in the Cordillera Blanca. The geomorphic evidence for the nature, magnitude and consequences of this event was investigated in August 2002. Field mapping indicated that the avalanche deposited $8\text{--}20 \times 10^6 \text{ m}^3$ of rock into the lake and onto the surface of the frontal region of Glaciar Pucajirca, which flows into the lake. Repeated bathymetric surveying indicated that $\sim 5 \times 10^6 \text{ m}^3$ of this material was deposited directly into the lake. The immediate effect of this event was to create a displacement wave that gained in height as it travelled along the lake basin, overtopping the impounding moraine at the lake's northern end. To achieve overtopping, the maximum wave height must have been greater than 100 m. This, and subsequent seiche waves, caused extensive erosion of both the proximal and distal faces of the impounding terminal moraine. Further deep gullying of the distal face of this moraine resulted from the supply of pressurized water to the face *via* a relief overflow tunnel constructed in 1978. Two-dimensional, steady-state analysis of the stability of the post-avalanche moraine rampart indicates that its proximal face remains susceptible to major large-scale rotational failure. Copyright © 2005 John Wiley & Sons, Ltd.

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Introduction

Proglacial lakes dammed by arcuate, terminal moraine ridges pose a potential threat to communities in high mountain regions, particularly in relatively heavily populated lower latitude areas. These lakes form between the frontal margins of receding glaciers and terminal moraine ridges formed by those glaciers during an earlier advance, often the Neoglacial maximum reached between the mid-19th and early 20th centuries. Importantly, present-day climatic warming is causing many of these glaciers to retreat rapidly (see, e.g., Kaser and Osmaston, 2001). Consequently, there is a corresponding increase in the rate of formation of potentially-hazardous moraine-dammed lakes (Ames, 1998). Such lakes develop as an end member of a spectrum of forms that commonly begins with the coalescence of supraglacial ponds on the decaying tongues of these often shallow, debris-mantled glaciers (Reynolds, 2000; Benn *et al.*, 2001).

The principal hazard posed by moraine-dammed proglacial lakes is that of catastrophic outburst floods resulting from a breach of the moraine dam. Such failures and their geomorphic effects have been reported from numerous

locations, including the Himalayas (see, e.g., Watanabe and Rothacher, 1996), central Asia (see, e.g., Popov, 1990), Canada (reviewed by Clague and Evans, 2000), North America (see, e.g., O'Connor and Costa, 1993) and the Andes (see, e.g., Reynolds, 1992). In Peru, related events (termed *alivi6nes*) have claimed the lives of some 32 000 people in the past 100 years (Lliboutry *et al.*, 1977a; Reynolds, 1992). Because some of these moraine dams are ice cored, they are naturally subject to ice degradation (Richardson and Reynolds, 2000). This degradation is of particular concern in environments experiencing enhanced climatic warming. Although little is known about the processes of dam breaching, these potentially catastrophic events are most commonly triggered by earthquakes or the impact of displacement waves induced by rock, ice or snow avalanches or calving from receding ice cliffs into proglacial lakes, or a combination of these processes. Thus, it is generally accepted that as climate-driven glacier recession and moraine degradation accelerates, so the frequency of *alivi6nes* will increase (Reynolds, 1998).

Despite numerous studies (above) reporting the occurrence and effects of glacial lake outburst floods, there is a general absence of information relating to the processes that can cause dam wall failure. The aim of this paper is to address this issue by reporting the geomorphic effects of a rock avalanche that fell into Laguna Safuna Alta, Cordillera Blanca, Peru, in April 2002. That this avalanche did not result in the failure of the retaining dam wall is fortuitous, not only because a catastrophe may have been averted, but also because much of the erosive and depositional evidence relating to the event was not removed by an outburst flood. In this paper we use this evidence to investigate the nature of the avalanche, the effects of the avalanche on the Laguna Safuna Alta and its immediate environment and the consequences of those effects for the stability of the surviving moraine rampart.

Field Site

Two Safuna lakes, the upper and lower (Laguna Safuna Alta and Laguna Safuna Baja respectively), are located adjacent to the terminus of Glaciar Pucajirca, which flows off the north side of Nevados Pucajirca in the northern part of the Cordillera Blanca, Peru (Figure 1). Laguna Safuna Alta is in contact with, and extends immediately to the north of, the terminus of Glaciar Pucajirca at an altitude ~4355 m above sea level (a.s.l.). Laguna Safuna Baja is located ~80 m lower and ~0.5 km further down valley to the north. The lakes are separated by a large terminal moraine rampart that dams the Laguna Safuna Alta. This innermost moraine is the most recent of a sequence of moraines that bound both lakes (Lliboutry *et al.*, 1977b), and its lateral extension encloses three margins of the upper lake. On both sides of the valley, these inner lateral moraines (which are vegetated on their distal faces but not on their proximal faces) rest against older lateral moraine ridges. The terminal and lateral moraines damming Laguna Safuna Baja are now degraded and well vegetated, but they remain up to 60 m high on their distal side. Below the lakes, the waters join those draining the north-eastern side of Nevado Alpamayo and flow north-eastwards down the valley of the Quebrada Tayapampa, which is populated by scattered homesteads and principally used for livestock grazing and trekking-based tourism. Approximately 24 km downstream, this river narrows to flow through the Quitaracsa gorge and the valley enters the Cordillera Blanca's principal river, the Rio Santa, ~40 km downstream. The confluence with the Rio Santa occurs close to the sizeable village of Huallanca and its hydroelectric power station. Both population and infrastructure are therefore at risk if a flood were to be generated at the site of the Safuna lakes.

Geological setting

The Safuna region is principally underlain by Mesozoic sedimentary rocks with more recent intrusions of granodiorite to the south and west, and with a patchy cover of Holocene glacial and glaciofluvial surficial deposits (Wilson *et al.*, 1995). The core of a major syncline is located ~2 km east of the Safuna lakes, with its axis aligned NW–SE, sub-parallel to the orientation of the Safuna lakes and upper valley. This feature extends to the eastern flank of the Safuna valley, and is formed of Lower Cretaceous limestones, calcareous mudstones, mudstones and sandstones. Underlying quartzites, sandstones and mudstones are exposed on the western side of the Safuna valley. To the south-west, sedimentary formations are intruded by the granodiorites and tonalites of the Cordillera Blanca batholith that form much of the western and central parts of the range. Glacier ice and glaciofluvial deposits dominate the surface geology immediately south of the Safuna lakes.

Recent history

Aerial photographs from 1950 indicate that Glaciar Pucajirca extended to its Neoglacial terminal moraine at that time, and that Laguna Safuna Alta had therefore not yet formed. However, a series of supraglacial ponds is visible on the northeastern part of the glacier tongue in the pictures. Aerial photographs from July 1963 indicate that these ponds had

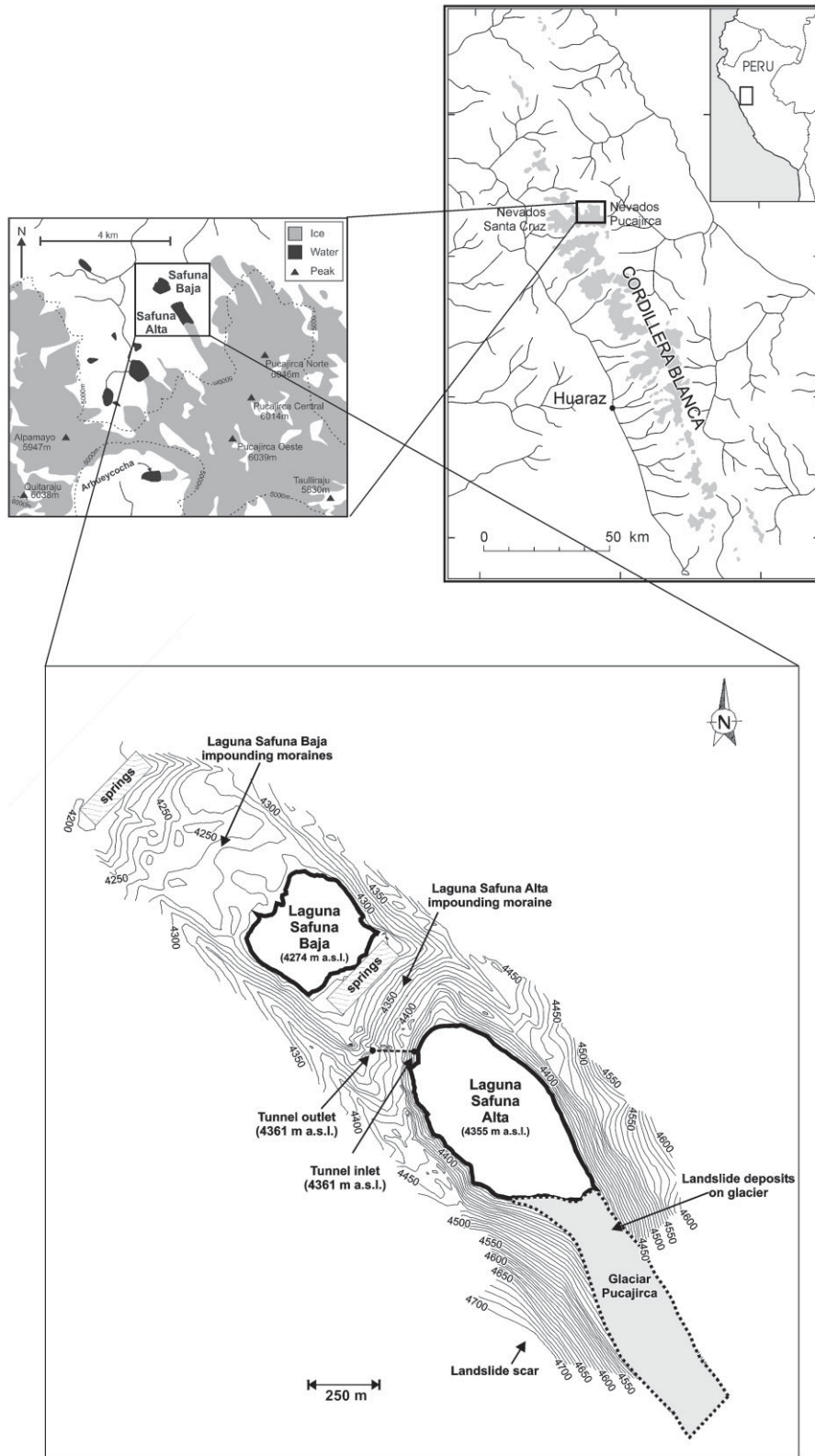


Figure 1. Location map of Laguna Safuna Alta and Laguna Safuna Baja, Peru.

coalesced by that time to form a small lake. This lake, named Laguna Safuna Alta, spread to the full width of the ice front during the 1960s. By the late 1960s, a topographic and bathymetric survey carried out by the Peruvian National Institute of Natural Resources (INRENA) indicated that the volume of Laguna Safuna Alta had reached $6 \times 10^6 \text{ m}^3$. The surface level of the lake at that time was close to 4380 m a.s.l., 25 m above the present level and 105 m above the level of the Laguna Baja. With no obvious channelized outflow, the size and rapid development of Laguna Safuna Alta caused considerable concern and, in order to limit any further rise in water level, a tunnel was excavated through the moraine a little above the level of the lake surface. Soon after this tunnel was completed in early May 1970, it was badly damaged in the devastating earthquake of 31 May of that year. However, the earthquake also caused a drop in the level of the lake of ~25 m. Although the rate at which this surface drop occurred is not known, the fall presumably reflects an increase in the bulk permeability of the moraine dam. When the lake was resurveyed by INRENA personnel in 1973 its volume had decreased to $2 \times 10^6 \text{ m}^3$.

Glaciar Pucajirca receded sharply through the 1970s. Mass balance studies reported by Lliboutry *et al.* (1977b) indicated that the equilibrium line altitude at this time was ~5000 m a.s.l. This led to an increase in the area of the upper lake, although its surface elevation remained broadly constant. In 1978, a second tunnel was bored ~5 m above the contemporary lake level to preclude any subsequent rise in the water surface. Since that time, the glacier has continued to recede and the area of the lake has continued to increase. However, the lake's water level has still not changed significantly and the new tunnel was not called into operation until the events described below occurred in 2002. A survey carried out in 2001 indicated that the lake was ~1200 m long and ~120 m deep at its deepest point. Its volume had increased to $\sim 21.3 \times 10^6 \text{ m}^3$ (Figure 2). At that time the moraine dam provided ~80 m of freeboard at its lowest point and ~100 m of freeboard for most of its length.

On 22 April 2002, a rock avalanche fell from the western valley-side slopes onto the surface of the terminal region of Glaciar Pucajirca and into the southern end of the Laguna Safuna Alta. The effects of this event were investigated in early August 2002, and are summarized below.

The Rock Avalanche of 22 April 2002: Field Evidence

Avalanche properties

In August 2002, the avalanche scar and rock deposits were clearly visible from the air (Figure 3(a)), as was extensive fresh erosion of the surface of the impounding moraine dam. Exposed rock slopes in the area of the avalanche scar consist largely of quartzite with sub-vertical foliation that strikes parallel to the long axis of the valley (approximately 145°). Extensive tension cracking was observed in a zone between 100 and 150 m wide located to the rear of the crest of the slip and to the north of the centre of the slip, at an altitude close to 4700 m a.s.l. These cracks ranged in width from 75 mm to 2 m and were observed to a depth of >6 m (Figure 4). A major back scarp, with a throw of 5–6 m, is located at an altitude close to 4720 m a.s.l. in the north, rising to 4745 m a.s.l. in the centre of the existing slip zone. This scarp marks the rear of the highly disturbed area, although some smaller subsidiary tension cracks are visible to the rear of this feature up to an altitude of around 4800 m a.s.l.

Field mapping of the avalanche scar by Global Positioning System indicates approximate dimensions of ~400 m high, 400–500 m wide and 50–100 m deep. These dimensions indicate a maximum slide volume of $8\text{--}20 \times 10^6 \text{ m}^3$, which suggests a rock mass of $\sim 22\text{--}54 \times 10^9 \text{ kg}$.

Rock avalanche effects on Glaciar Pucajirca

Avalanche debris that fell onto the glacier tongue forms a deposit that crosses and obscures the full width of the ice surface (Figure 3(b)). The dimensions of this deposit were estimated to be 300–400 m along-glacier, 200 m across-glacier, and up to 40–50 m thick. These dimensions equate to a debris volume of $2\text{--}4 \times 10^6 \text{ m}^3$, or, assuming a bulking factor of 1.5 (i.e. host rock has a density of 1.5 times that of the unconsolidated debris deposited on the glacier surface), ~10–30% of the volume of rock estimated to have been delivered from the avalanche scar (equating to a mass of $\sim 4\text{--}7 \times 10^9 \text{ kg}$). Investigation of the northern (i.e. lake-ward) slopes of the landslide debris revealed the presence of numerous linear, shore-parallel features, defined by stranded vegetation and back scarps.

Rock avalanche effects on Laguna Safuna Alta

A topographic and bathymetric survey of Laguna Safuna Alta was carried out in August 2002 (Figure 2(b)). Comparison of this survey with that recorded immediately prior to the avalanche in 2001 (in contoured planform in

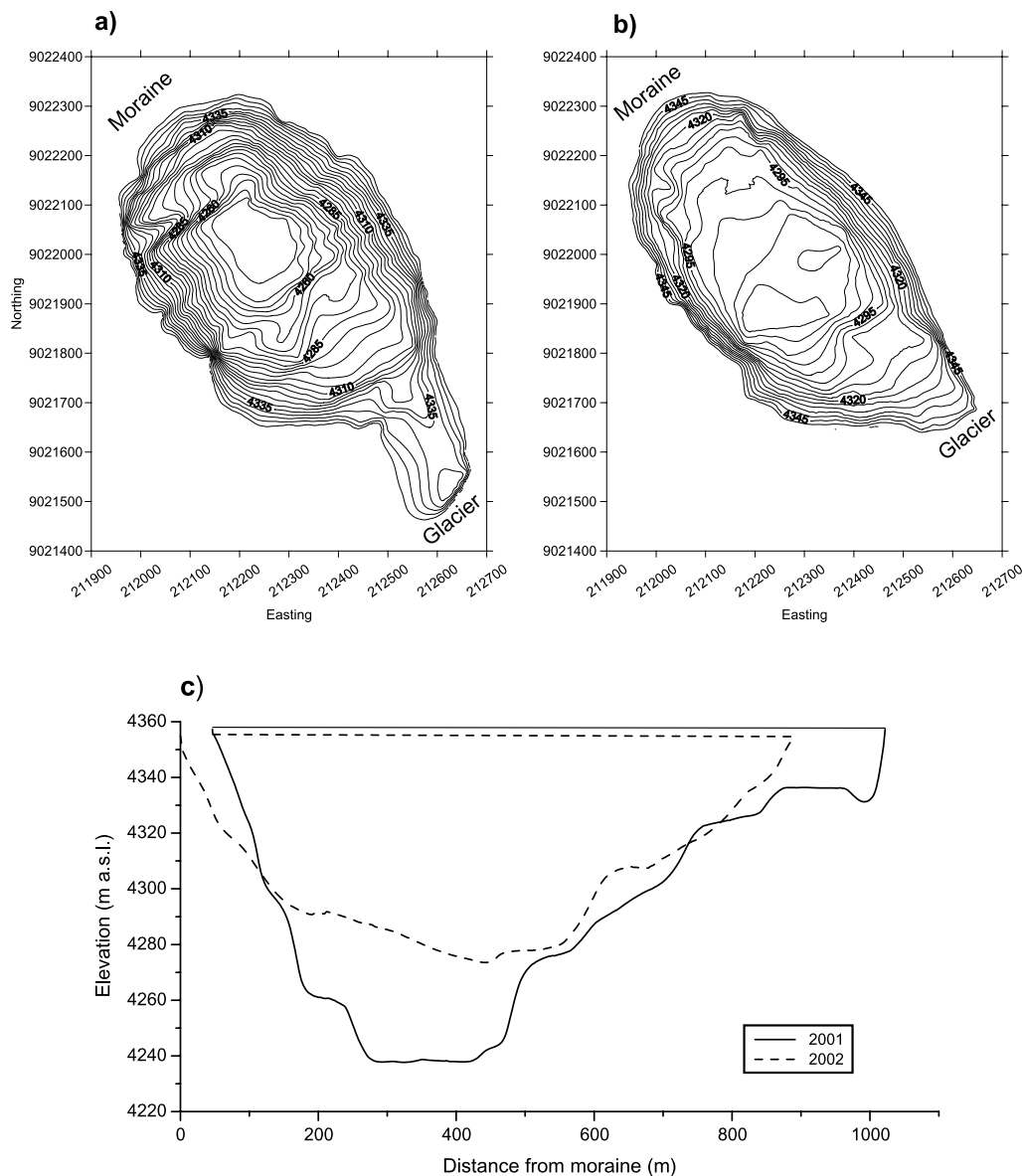


Figure 2. Bathymetric maps (contour interval of 5 m) of Laguna Safuna Alta (a) in 2001 (prior to the avalanche) and (b) in 2002 (following the avalanche), and (c) long sections through the two basins. The planform location of this long section is marked in Figure 5.

Figure 2(a) and in centerline long section in Figure 2(c)) revealed that the lake's maximum depth was reduced from ~120 m in 2001 to ~81 m in 2002. The location of the deepest point has also shifted towards the south-east, the deepest point in 2001 having been reduced in depth by almost 50 m. These patterns of change may be visualized by superimposing the 2002 lake outline onto the 2001 lake outline and contouring the difference in bathymetry between the two, calculated as elevation in 2002 minus elevation in 2001 (Figure 5). As anticipated, most of the basin has been filled in, with the greatest amount of accretion occurring in the deepest part of the pre-avalanche basin. In addition, the south-eastern section of the lake where it abutted the glacier has been filled in completely by avalanche material, reducing the lake's surface area by ~150 m × 200 m (marked **A** in Figure 5). Material has also been deposited along both lateral moraines of the basin, effectively reducing the lake's width by between 50 and 100 m along most of its length (marked **B** in Figure 5). Given the location of this material, it is likely that much of it was derived from erosion

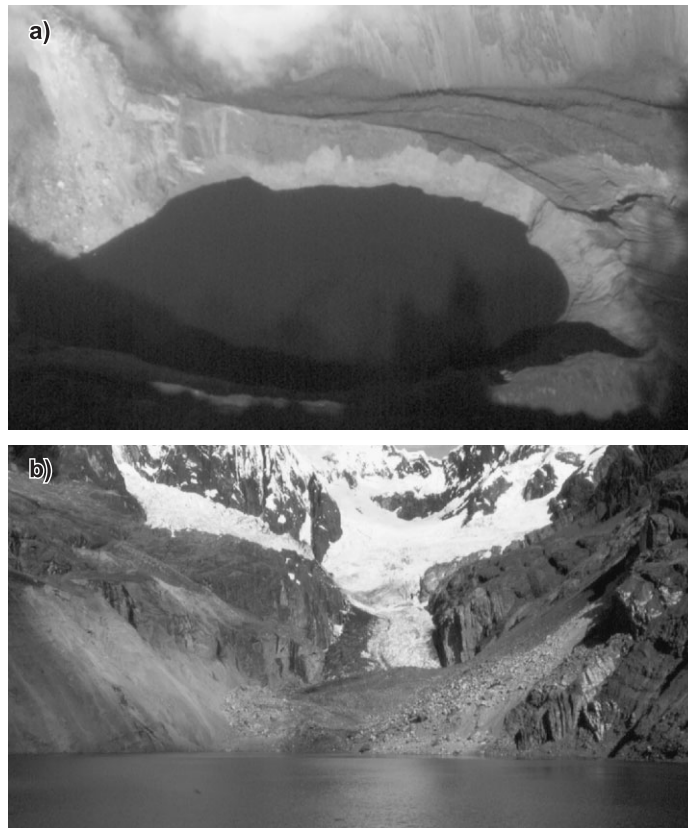


Figure 3. Photographs of (a) the avalanche scar and associated erosion viewed from the air, and (b) the avalanche deposit on the surface of Glaciar Pucajirca and in the southern end of Laguna Safuna Alta.

higher up the basin's lateral moraine flanks rather than from the avalanche. Finally, it is worth noting that the lake surface has extended its northern margin by eroding into the terminal moraine dam wall by up to ~40 m (marked C in Figure 5).

Despite depositing a large amount of material into the lake (and displacing an equivalent volume of water), the lake's long-term water level has not risen to the height of the inflow of the 1978 relief tunnel. Indeed, the 2002 survey indicates that the lake level has fallen by ~2 m relative to 2001 (to 4355 from 4357 m a.s.l.). Correspondingly, the lake's volume decreased by $\sim 5.5 \times 10^6 \text{ m}^3$ as a result of the event, from $21.3 \times 10^6 \text{ m}^3$ in 2001 to $15.8 \times 10^6 \text{ m}^3$ in 2002.

Rock avalanche and seiche effects on the moraine dam – proximal slope

The moraine dam was observed to consist predominantly of gravel-sized material, with a strong representation of boulder-sized and sand-sized debris. Only a very minor quantity of silt-sized material was observed. Clast shape within this sandy boulder gravel is highly variable, ranging in shape from sub-rounded to angular, and with some clasts being striated and faceted, indicating subglacial transport, and others being more typical of rockfall debris. At the scale of metres to tens of metres, crude stratification by grain size and sorting was observed. The detailed internal structure and sedimentology of the moraine, and others in similar settings, are the subject of ongoing study.

The base of the proximal slope of the lateral impounding moraine is marked by a widespread surface exposure of relatively light-coloured debris that contrasts with darker weathered surface material present at higher elevations. The surface of the lighter zone is composed of fresh debris and is devoid of any vegetation or soil development, in contrast to the overlying darker material which shows evidence of soil development and has scattered lichen, moss and grass. The boundary between the two zones is marked by a steep ledge of varying height separating the higher, darker-coloured material from the lower lighter-coloured material. This boundary rises in elevation along both lateral inner

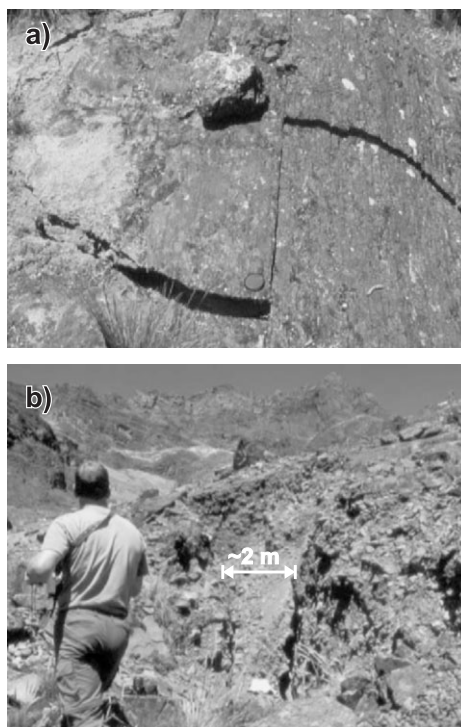


Figure 4. Photographs of (a) small (note lens cap for scale) and (b) large tension cracks in the terrain above and to the north of the existing avalanche scar immediately to the south-west of Laguna Safuna Alta.

walls of the lake basin, away from the southern end of the lake, where the landslide entered the water (Figure 6). This rise in elevation continues until the lighter zone intersects the crest of the moraine near the northern end of the lake. Close inspection within the lighter zone of the proximal terminal moraine slope reveals the presence of a series of up to ten linear surface discontinuities. Each of these is marked by a slight ledge, similar to that between the uppermost limit of the lighter zone and the overlying darker zone, consistent with the relative removal of material below each discontinuity. Each of these ledges can be traced for lateral distances of tens to hundreds of metres, often across the entire face of the moraine. Within this zone, the concrete lining of the 1978 relief tunnel (which was flush to the moraine face until 2001) was observed to protrude from the face by ~ 4 m in August 2002.

Topographic surveying indicates that much of the slope area within the light coloured zone has gradients between 50° and 56° . A major slump can be identified across a broad zone of the eastern end of the terminal moraine. In other areas, markedly over-steepened sections have been created; in particular, a narrow gully immediately to the west of the 1978 portal stood in August 2002 at an angle of $\sim 70^\circ$. Local stone-fall occurred frequently from this area during fieldwork. Extensive tensional cracking was also observed on either side of this gully, while the crest above was highly unstable. Cracking was also observed elsewhere at intervals along the crest of the moraine.

The light-coloured zones are interpreted to be areas of fresh erosion created by seiche action. This interpretation is discussed in more detail below.

Rock avalanche and seiche effects on the moraine dam – distal face

Prior to the 2002 avalanche, the distal face of the terminal moraine was heavily vegetated with grasses and shrubs. The majority of this vegetation and surface soil had been removed by August 2002 (Figure 7(a)), and the lateral limits of this erosion coincided with the uppermost limit of the light-coloured zone on the proximal face. Close examination of the distal face, however, indicated a zone about 5 m wide immediately below the crest of the moraine that remained heavily vegetated. Damage immediately below this strip was severe, and marked in many areas by local steepening of several degrees in addition to the removal of surface vegetation and debris. In some places, erosion scars were present on this distal flank which generally stands at angles of between 36° and 40° , although angles of between 22° and 50°

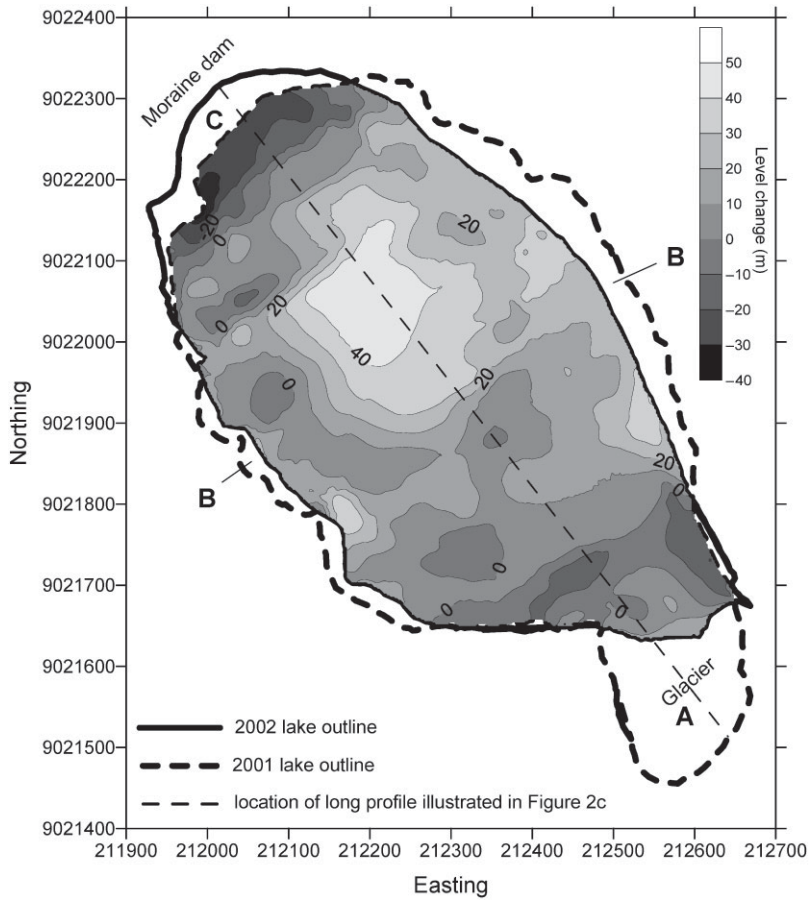


Figure 5. Surface outlines of Laguna Safuna Alta in 2001 (prior to the avalanche) and 2002 (following the avalanche) and a contour plot of the change in basin elevation in overlapping areas. Descriptions of the areas marked A, B and C are provided in the text. The dashed line indicates the location of the profile illustrated in Figure 2(c).

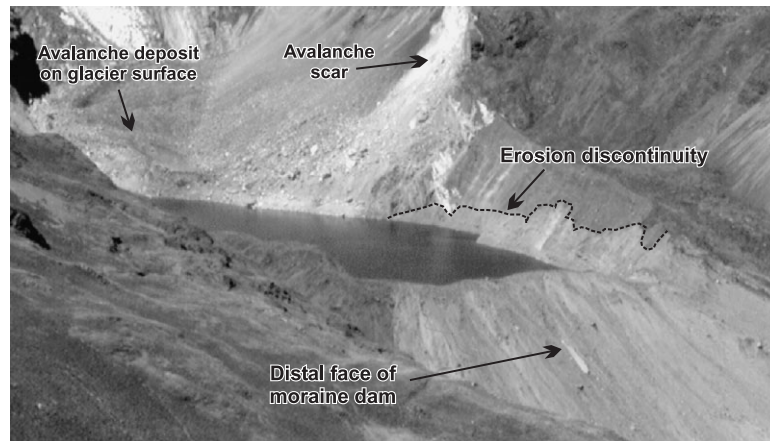


Figure 6. Photograph of Laguna Safuna Alta and its immediate surroundings taken in August 2002. Note the rise in the level of light-coloured surface material (marked as 'erosional discontinuity') along the inner slopes of the lake basin away from the avalanche deposit, also visible in Figure 3(a).

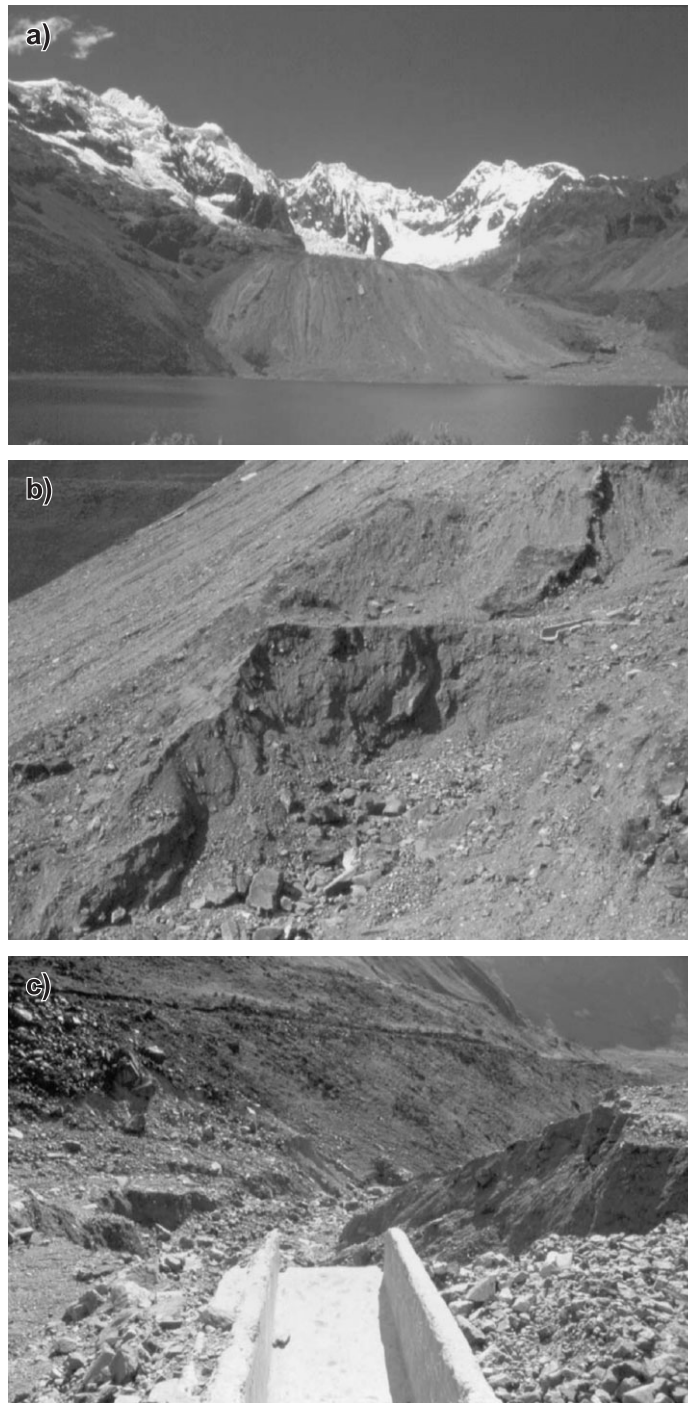


Figure 7. Photographs of the distal face of the terminal moraine dam at Laguna Safuna Alta: (a) general view (note the widespread removal of vegetation, indicated by a lighter colour, from the moraine face), (b) view of the deep gully formed below the remains of the outlet of the 1978 relief tunnel (top right) and (c) view along the end of the damaged outlet of the 1978 relief tunnel, from where an additional ~15 m long concrete spillway has been eroded.

were measured. The steeper angles are primarily associated with a deep and freshly eroded gully located below the outflow of the 1978 overflow tunnel (Figure 7(b)). This gully, which was not present in 2001, extends to the lower part of the distal face of the moraine, forming a debris fan where it enters the Laguna Safuna Baja (Figure 7(a)). The carcasses of 22 cattle, each with signs of severe physical trauma, are located on and within this debris fan. A shallower gully exists in the upper part of the distal face of the moraine dam, above the portal of the 1978 tunnel.

Even more damage was apparent to the outlet of the 1978 relief tunnel than to its inlet. At its outlet, a 15 m long concrete spillway structure was completely removed and under-cut by the deep erosion gully (Figure 7(c)). However, the interior of the tunnel appeared pristine when inspected in August 2002, containing no debris and showing no signs of interior erosion. At one location, a small fragment of the wooden formwork was observed still attached to the roof.

Rock avalanche effects on Laguna Safuna Baja

The proximal flanks of lateral moraines associated with Laguna Safuna Baja are well vegetated to the shoreline of the lake. However, there was evidence in August 2002 of damage arising from the overspill of the displacement wave(s) from Laguna Safuna Alta in the form of broken and uprooted vegetation and a veneer of fine sediment up to ~2.5 m above the August lake level.

The Rock Avalanche of 22 April 2002: Interpretation

The relationship between the avalanche scar and the rock beds exposed in its base indicate that the slope failed by the bending forward and fracture of rock columns separated by well developed, steeply dipping discontinuities, known as flexural toppling. The delivery and presence of $4\text{--}7 \times 10^9$ kg of material onto the surface of Glaciar Pucajirca has implications for the mass balance and dynamics of the glacier. Although these implications remain unknown until further data are collected, one would expect ablation in the debris-covered area to be reduced, and therefore for the current mass balance (which has been strongly negative) to become less negative as mass is less readily lost by surface melting in the lower terminus region of the glacier. Some reduction in the rate of retreat of the glacier is therefore likely. However, the associated reduction in the delivery of meltwater to the lake is also likely to lead to a fall in lake level, partially reducing the hazard posed by the system. Finally, the mechanical impulse provided by the impact of this mass of rock would have marked implications for the immediate structural stability of the glacier as well as for the glacier tongue's stress field in the medium term.

The basin of Laguna Safuna Alta has clearly been affected by the delivery of avalanche debris to the lake. However, basin filling is evident some distance from the location of the avalanche at the southern end of the lake, suggesting that not all of the infilling material was supplied directly by the avalanche. Patterns of aggradation are consistent with some of this material being supplied by erosion of the proximal slopes of the impounding moraine dam. Thus, the net effect of the avalanche on the lake was to reduce its volume by depositing (and inducing the deposition of) approximately 5×10^6 m³ of material into its basin. Despite this infilling, the long-term lake level changed by only 2 m relative to before the event, indicating a reduction in the volume of the lake. This suggests that the terminal moraine's bulk hydraulic conductivity has been altered only to a very minor degree (indeed, possibly increased slightly) as a result of the avalanche.

Deposition in the lake basin of material from the proximal slopes of the impounding moraine is further supported by our interpretation of the lighter-coloured area on the moraine's surface as a zone of fresh erosion. In this case, the general rise in the uppermost limit of this zone marks the passage of an initial, avalanche-induced displacement wave. This wave initiated at water level at the southern end of the lake and continued to rise as the basin narrowed towards the moraine dam. The intersection of this boundary with the crest of the terminal moraine implies that at least one wave overtopped the full width of the moraine dam, indicating that the maximum height of the initial displacement wave was greater than 100 m. The preservation of a strip of vegetation just below the crest of the moraine on its distal face is consistent with this wave becoming airborne for a short distance as it passed over the crest, before causing particularly marked erosion upon recontacting the distal face.

The numerous linear discontinuities located below the upper limit of the eroded zone on the proximal face of the moraine are interpreted as the run-up limits of a decaying sequence of seiches formed as the initial displacement wave oscillated backwards and forwards in the enclosed basin. This sequence is consistent with the presence of multiple strand-lines on the avalanche material on the surface of Glaciar Pucajirca at the northern end of the lake. These patterns suggest that the primary overtopping wave eroded the proximal and distal faces of the moraine dam. The resulting water-debris mixture caused extensive erosion to the exposed inlet and outlet portals of the 1978 tunnel.

However, the initial wave impact appears to have injected a relatively small amount of (probably debris-poor) water through the tunnel itself. The small water volume might be explained by the protection afforded by the concrete balcony extending from the tunnel inlet (which was severely eroded by the wave) and the angle of flow of the wave past the tunnel entrance (the face is locally inclined at an angle of $\sim 50^\circ$ to the dip of the tunnel). Similarly, the erosion of the tunnel outlet is interpreted to have been achieved by the water that overtopped the moraine, initiating gully erosion along the full height of the distal face. Subsequently, the level of Laguna Safuna Alta would have been intermittently raised above the 1978 relief tunnel during the passage of the decaying seiches. Indeed, the steady-state water level after the avalanche was almost certainly temporarily raised above the tunnel entrance solely as a result of water displacement by the avalanche material deposited into the lake. During periods when the tunnel entrance was submerged by the seiche waves, water would have flowed under high pressure through the tunnel and been ejected from its outflow. This water, although initially free of debris (hence the absence of significant erosion to the inner walls of the tunnel), was responsible for extending the gully below the tunnel exit on the distal face. Indeed, close inspection of this gully indicates the presence of several nested gullies, each of which may have been formed by pressurized flow associated with the passage of a seiche (Figures 7(b) and 7(c)).

Dam Wall Stability Following the Rock Avalanche

The steady-state stability of the moraine dam following the erosion associated with the April 2002 event was examined using a geotechnical software package, SLOPE/W (GEO-SLOPE International Ltd), which uses limit equilibrium theory (Fredlund and Krahn, 1977) to compute the factor of safety of earth and rock slopes. The analysis was carried out for circular slip surfaces, based principally on the method of Janbu *et al.* (1956). Calculations were carried out on the proximal and distal faces of a cross-section through the moraine dam drawn on the basis of the August 2002 survey data. The plane of the cross-section is located immediately west of the 1978 tunnel inlet and was selected so as to include steep gullies in both the proximal and the distal faces. In addition to cross-sectional geometry, this (steady-state) two-dimensional analysis requires strength properties of the material forming the moraine dam (specifically, effective cohesion c' and angle of internal friction ϕ') and its water table level. The intersection of the water table with the proximal and distal faces of the moraine are assumed to be represented by the lake level measured in August 2002 and the elevation of the line of springs emerging from the base of the moraine's distal face respectively. For the purposes of the analysis, the moraine dam is assumed to be composed of a single material type, the cohesion and internal angle of friction of which are bracketed to include realistic values based on those calculated from similar materials sampled from terminal moraine dams in Nepal (Table I). The values adopted for these properties are a unit weight of 21 kN m^{-3} , an effective cohesion of 5 kN m^{-2} (bracketed by values of 2 and 8 kN m^{-2}) and an angle of internal friction of 38° (bracketed by values of 35 and 41°). The analysis was carried out to identify the

Table I. Computed factors of safety for small and large failures on the proximal slope and distal slope of the terminal moraine impounding Laguna Safuna Alta for different moraine strength parameters (described in the text). The results presented in bold represent the outcome in response to the most probable strength parameter values

| Strength parameters | | Factor of safety | | | |
|-----------------------------|----------------------|------------------|-------------|--------------|-------------|
| | | Proximal slope | | Distal slope | |
| c' (kN m^{-2}) | ϕ' ($^\circ$) | Small | Large | Small | Large |
| 2 | 35 | 0.49 | 0.65 | 0.78 | 1.31 |
| 2 | 38 | 0.54 | 0.72 | 0.86 | 1.46 |
| 2 | 41 | 0.58 | 0.81 | 0.96 | 1.62 |
| 5 | 35 | 0.60 | 0.68 | 0.86 | 1.32 |
| 5 | 38 | 0.66 | 0.75 | 0.94 | 1.47 |
| 5 | 41 | 0.72 | 0.83 | 1.03 | 1.64 |
| 8 | 35 | 0.65 | 0.70 | 0.93 | 1.34 |
| 8 | 38 | 0.71 | 0.77 | 1.02 | 1.49 |
| 8 | 41 | 0.78 | 0.86 | 1.11 | 1.65 |

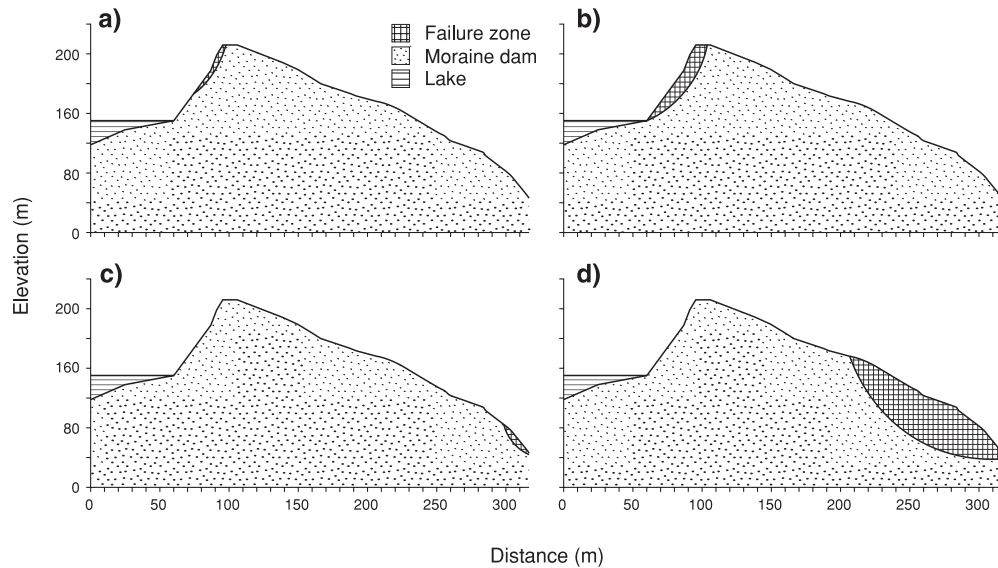


Figure 8. Calculated rotational slip surface geometries in the terminal moraine at Laguna Safuna Alta, in cross section, associated with the minimum factors of safety presented in Table I: (a) proximal face, small slip; (b) proximal face, large slip; (c) distal face, small slip; (d) distal face, large slip.

factors of safety associated with the smallest failure possible on both the proximal and distal faces (termed small failure) and for large failures on each slope. In the latter cases, the large failure on the proximal slope is defined as that which affects the full height of the slope and the large failure on the distal slope is defined as that which crosses the piezometric line.

The results of the stability analysis, summarized in Table I, indicate that the most likely minimum factor of safety against a small failure on the proximal face is 0.66 (Figure 8(a)) and that against a large failure on the same face is 0.75 (Figure 8(b)). Because both values are less than unity (where a value of unity indicates that the forces maintaining the stability of the slope are equal to those destabilizing the slope) the analysis predicts that the proximal face was, in August 2002, following the avalanche and seiche, unstable to both small and large rotational failures. In contrast, the factor of safety calculated against a small failure on the distal slope is 0.94 (Figure 8(c)), while that against a major failure is 1.47 (Figure 8(d)). The former narrowly indicates instability, while the latter indicates stability.

In addition to this analysis, an inverse analysis was performed to find what parameters of c' and ϕ' would be required to result in a factor of safety of unity on the proximal face, i.e. the minimum required to predict stability. It was found that if ϕ' is 45° then c' must be 15 kN m^{-2} and if ϕ' is 48.5° then c' must be 10 kN m^{-2} . Neither of these combinations of values (which are all exceptionally high) is realistic, and the analysis therefore clearly indicates that, even under static conditions, the moraine dam cannot be considered stable. If a seismic event or additional displacement wave were to occur, then the stability of the proximal face of the dam would be less stable than the analysis indicates.

Discussion

Likelihood of rock avalanche recurrence

Inspection of the slope adjacent to the rockfall of 22 April 2002 revealed a large number of active back scarps and tension cracks. Rock strata at the toe of the northern end of the landslide are generally sub-vertical, but become severely overhanging higher up this exposure and towards the back scarp of the landslide itself. There can be little doubt that the potential exists for another large-scale failure. The extent of the fractured area is perhaps half as extensive as that affected by the rock avalanche of 22 April 2002, potentially resulting in an avalanche of volume of $\sim 5 \times 10^6 \text{ m}^3$, yielding $\sim 13 \times 10^9 \text{ kg}$ of rock. Given the location of the unstable ground in relation to the tongue of Glacier Pucajirca, it is likely that a high proportion of any future rock avalanche material would fall directly into the lake.

Likelihood of moraine dam failure

The moraine dam and lower lake resisted and contained the 2002 event, which is estimated to have been bigger than any rock avalanche likely to occur in the near future. However, there can be little doubt that the dam is now weaker than it was prior to the 2002 event, and that more of the debris in a future avalanche would fall directly into the upper lake. The stability analyses indicate that the proximal face of the moraine dam is very likely to experience large-scale failure if such an event occurs. The consequences of such a failure are not known. Given the deep gully eroded in the distal face, it is possible that a major rupture of the entire moraine could result from a large failure on the proximal slope. However, the low factors of safety recorded in relation to smaller events on both faces of the moraine indicate that continued smaller failures may well gradually degrade these slopes to shallower, and therefore more stable, angles over some years. Further, the present steady-state water level in the basin is below the lower limit of any predicted failure, with the consequence that even a major rupture might result in no, or very limited, water escape other than that caused by seiche action. It is important to note, however, that several additional factors serve to increase the hazard risk. First, the failure analysis assumes static conditions and does not account for additional transient destabilizing influences such as those resulting from seismic events or wave impacts. Second, the analysis considers the moraine dam to be composed of homogeneous material containing no large-scale heterogeneity or planes of structural weakness. Although no systematic research has yet been carried out on the large-scale structural composition of moraine dams such as the moraine at Safuna, it is clear from field observations within the newly eroded gully on the distal face that the moraine is structurally complex and composed of several sediment facies. However, the presence of the lower lake and its impounding moraines would act as a major buffer to any potentially catastrophic delivery of material from the upper lake at Safuna. Indeed, the lower lake absorbed the entire overflow from the upper lake resulting from the events of 22 April 2002. As noted above, this water delivery caused a temporary rise in the shoreline of the lower lake of ~2.5 m, equating to a transient increase in volume from ~634 000 m³ to ~915 000 m³. Further, the lowest overflow from the lower lake is ~7 m above its current level (measured at ~4281 m a.s.l. in August 2002), indicating a potential total lake volume of over 16 000 000 m³. It is also unlikely that the impounding moraine sequence of the lower lake would be easily breached by a high magnitude event since it is shallow sided and extends for some 700 m down valley (Figure 1).

Further research

The events of 22 April 2002 reconstructed above are both remarkable and informative. Clearly, the rock avalanche and its displacement wave(s) presented a very real threat to the integrity of the moraine rampart that impounds Laguna Safuna Alta. The possibility of such failures here and elsewhere demands that we gain a comprehensive understanding of the processes controlling their likelihood. Our research at Safuna points to several areas for future investigation, both at this site and elsewhere.

- The medium-term effects of the presence of several million tons of avalanche debris on the surface of Glaciar Pucajirca are not known. A glacier advance could have major implications for the level of Laguna Safuna Alta and the stability of its terminal moraine. Mass-balance and geometrical surveys could therefore usefully be carried out to monitor and evaluate the glacier's response over the forthcoming few years.
- Strategies need to be considered and implemented to reduce the risk of failure of the moraine dam at Laguna Safuna Alta. These could include strengthening the moraine dam, repairing the existing overflow channels, driving a new overflow channel through the dam or even enhancing the buffering effect of Laguna Safuna Baja by increasing its capacity.
- The flow pathways that dictate the bulk hydraulic conductivity of the moraine dam at Laguna Safuna Alta are not known. It is important that the nature of this permeating flow is understood because the effective bulk hydraulic conductivity dictates the steady-state lake level and, if that level rises, the moraine's bulk stability decreases.
- The large and small-scale sedimentological structure of the moraine dam at Laguna Safuna Alta is unknown. While our field observations clearly indicate that the moraine is characterized by marked structural variability, it has not yet been characterized systematically. The presence of such variability, however, may exert a critical control over the bulk resistance of the moraine wall to failure, both in terms of its inherent strength and in terms of its bulk hydraulic properties.
- The daily, seasonal and annual hydrological balance of Laguna Safuna Alta is not known. The lake's steady-state water level is dictated by both inflow and outflow fluxes. While the latter is largely governed by the hydraulic properties of the terminal moraine (above), the former is sensitive to water supply from Glaciar Pucajirca. To date, no systematic study has been carried out to quantify the water balance of a moraine-dammed proglacial lake. An ultimate research aim should be to develop such a scheme and to integrate it with a glacier mass-balance and flow model.

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