IMPACT OF LARGE LANDSLIDES, MITIGATION MEASURES

Jean F. SCHNEIDER, Fabian E. GRUBER & Martin MERGILI

University of Natural Resources and Life Sciences (BOKU), Vienna, Peter-Jordan-Str. 70, 1190 Vienna, Austria

ABSTRACT

Besides existing landslide-dammed lakes there is evidence of former cases in the high-mountain areas of Europe, Asia and America. In the Holocene, large landslides have repeatedly dammed lakes. Numerous prehistoric, historic and recent cases are evident where the dams could not resist the pressure of the impounding water. The result were flood waves characterized by particularly high peak discharges and long travel distances, leading to disasters where interfering with populated lands downstream. Even though most dam failures occur in the early phase after formation, lakes may also drain suddenly at later stages. Case studies from Central Asia and Northern Pakistan are employed in order to exemplify the involved phenomena regarding dam formation, outburst mechanisms and flood wave propagation. A particular focus is put on discussing the options for disaster risk reduction and hazard mitigation.

Key words: *Attabad, computer modelling, flood wave, Hattian Bala, lake outburst flood, landslide dam, Siachen-Gayari, spillway*

INTRODUCTION

Natural dams of various types retain lakes in many areas of the world. Costa & Schuster (1988) point out that mainly landslide-dammed lakes, glacier ice-dammed lakes and late neo-glacial moraine dams are prone to fail and to produce potentially destructive lake outburst floods. Whilst much work has been done on glacial lake outburst hazards (Richardson & Reynolds, 2000), the present paper focuses on landslide-dammed lakes.

Landslides are common geomorphic processes in high mountain regions such as Central Asia. Whilst the direct impact of such phenomena on mountain communities is obvious, many landslides are only the starting point of process chains. The formation of landslide-dammed lakes is often a highly significant secondary effect (Clague & Evans, 1994; Casagli & Ermini, 1999). Such landslide dams may fail suddenly due to impact waves, internal or retrogressive erosion, resulting in potentially destructive flood waves downstream. Lakes may also drain stepwise or continuously, others persist for a long period of time. Costa & Schuster (1988, 1991) and Schuster & Evans (2011)
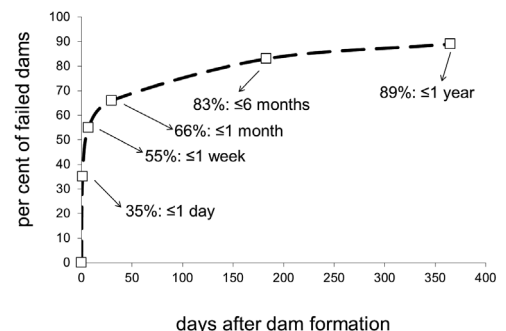

Fig. 1 - Percentage of failed dams plotted against the time after formation (after Schuster & Evans, 2011)

have shown that most dam failures occur in the first few months after the landslide event. Afterwards, the dam is usually consolidated so far that outburst floods become less likely (Fig. 1). However, impact waves triggered by mass movements into the lake may occur a very long time after dam formation.

Whilst geomorphic evidence indicates the existence and sudden drainage of landslide-dammed lakes in earlier stages of the Holocene, very recent cases have illustrated the huge challenge such phenomena pose for the population and the authorities of (possibly) affected areas.

The present paper is understood as a contribution to the understanding of the dynamics of landslide-dammed lakes and the challenges for risk mitigation in order to minimize future losses. The lessons learned from three recent cases from northern Pakistan (Hattian Bala, Attabad and Siachen-Gayari) are combined with historical and geomorphologic evidence from past events in Tajikistan and eastern Afghanistan. Fig. 2 shows the geographic location of the cases discussed below.

EVIDENCE OF FORMER EVENTS
LANDSLIDE DAMS IN THE TAJIK AND AFGHAN PAMIR
LAKE SAREZ

The highest natural dam known today, the Usoi Dam, has remained stable for more than 100 years now. It was formed by an earthquake-triggered landslide in 1911, blocking the Murghab Valley in the Tajik Pamir (see Fig. 2). Up to 600 m high, it impounded Lake Sarez, now 60 km long with a volume of 17 km³ (SCHUSTER & ALFORD, 2004). Since seepage through the dam almost offsets the inflow into the lake, the lake level rises only approx. 0.2 m per year
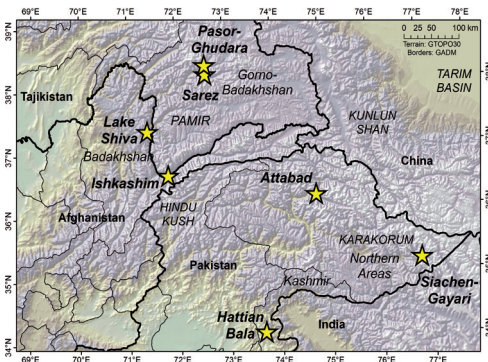
and has not yet reached the dam crest. Even though SCHUSTER & ALFORD (2004) list several possible failure mechanisms, there is still disagreement upon the level of hazard emanating from Lake Sarez. The dam is rated rather stable due to the consolidated structure, huge dimensions and the existence of a preferential, non-eroding flow path through the dam (ISCHUK, 2004, 2011). However, there is a creeping rock mass heading into the lake which, in case of sudden acceleration, could trigger an impact wave and consequent overtopping of the dam (RISLEY *et alii,* 2006). That rock mass, the dam and the Murghab River downstream are monitored and a flood early warning system was installed.

LAKE SHIVA

Lake Shiva has a maximum length of approx. 9 km and is located in the Shugnan District of northeast Afghanistan, at a distance of approx. 16 km from the south-west of Khorog, capital city of Gorno-Badakhshan, Tajikistan (see Fig. 2). It is impounded behind a natural composite dam across the valley of Arakht, a tributary of the river Panjwhich, in that region, constitutes the border between Afghanistan and Tajikistan.

A preliminary geological hazard assessment of the lake and dam was conducted by means of helicopter survey, satellite imagery interpretation and ground check in summer 2011. No immediate hazard of sudden drainage was detected, but a partial collapse of the dam due to retrogressive and piping erosion cannot be
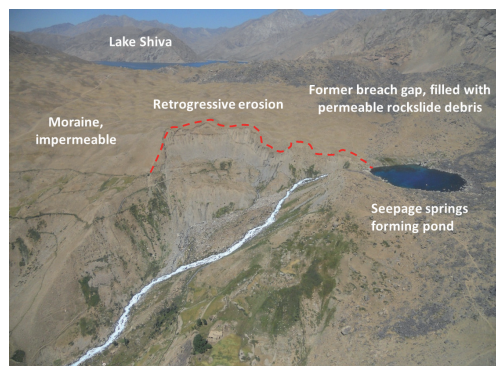

Fig. 3 - *Lake Shiva composite dam, view to the W. The depression spring (circular lake, diameter approx. 200 m) and headwater of Arakht torrent in the foreground; to the left of the lake the unstable part of the downstream side of the dam, with a band of much smaller springs, conspicuous because of spots of green vegetation. Moraine deposit in the centre, rock slide deposit in the right part of the photograph, the source of the rock slide is farther right*

Fig. 2   *Case studies discussed in the article*

completely ruled out. Subsequent flood wave modelling of two partial collapse scenarios have shown that in either case, in addition to all the villages on the way, the city of Khorog may be affected.

The dam retaining Lake Shiva is 1.6 km wide. Following SHRODER & WEIHS (2010) it is composed of the material of at least three landslides and a rock glacier. According to an assessment carried out by the authors the main part consists of a morainic dam, representing at least two late-glacial stages. This morainic dam, in its northern part, interdigitates with the deposit of a landslide which rushed down from the slopes to the north, presumably while the landscape had to accommodate the loss of its ice cover at the end of the last ice age. Perhaps a partial breach of the morainic dam did occur back then but if so, the gorge is now covered by landslide debris.

The dam has since consolidated, and obviously has never been overtopped by the impounded water in the shape it is now (after the possible first breakout). Instead, all the water supplied by the catchment is travelling through the dam by virtue of seepage, and for the most part is channelled through the permeable material supplied by the landslide. On the downstream side of the dam, part of the seeping water emerges in a stable depression spring, thereby creating a small circular lake (Fig. 3).

However, apart from the large spring with, stable piping, several additional springs have appeared on the downstream slope of the dam to the south of the main spring. This indicates seepage through the comparatively impermeable till constituting the main part of the dam. This has already led to retrogressive erosion of a currently rather small part of the dam affected by the seepage, and it is obvious that repeated slumping is taking place and retrogressive erosion is active (see Fig. 3). In case these instabilities continue, the dam - in the long run - could be weakened by erosion of its narrowest part, and also be undermined by concentrated seepage (piping).

Furthermore, SHRODER & WEIHS (2010) describe the dam site as situated at the crossing of two active tectonic lines, which could trigger local earthquakes.

PASOR - GHUDARA SYSTEM

Whilst Lake Sarez and Lake Shiva are prominent examples of still rather intact natural dams, the Pamir also bears a lot of evidence for failed dams. Several valleys were temporarily blocked by huge, predominantly coarse-grained deposits. Fine sediments upstream indicate lakes that have disappeared either by sedimentation or by sudden or stepwise dam failure. Even though the origin of these deposits is not undisputed and some may represent Pleistocenic moraines, many of them are identified as landslide deposits. One such example is located in the upper Bartang Valley (Central Pamir, Fig. 4a). The Pasor landslide dam, approx. 300 m high, blocked the valley and impounded the up to 8 km long Ghudara Lake. The age of the lake sediments was determined as ≤4000 years using Optically Stimulated Luminescence (OSL). After accumulating several tens of metres of lake sediments, the lake drained in stages and the sediments were deeply eroded. The narrow gorge through the landslide deposit may have been blocked several times. Downstream alluvial deposits, which are partly eroded leaving only remnant large blocks, indicate at least one powerful outburst flood (see Fig. 4b).

DASHT-SULAYMAN SYSTEM

The Panj Valley, forming the border between Tajikistan and Afghanistan (Wakhan Corridor), is partly blocked by the deposit of a debris avalanche at Dasht-Sulayman, upstream the town of Ishkashim
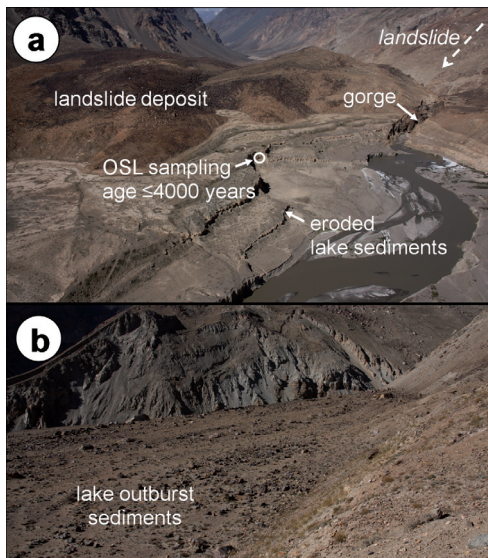

Fig. 4   (a) Pasor landslide (background) and eroded lake sediments in the foreground. The lake level dropped in several stages. (b) Partly eroded lake outburst sediments directly downstream of the dam showing typical outburst flood structures

(see Fig. 2). The origin of the landslide consisting of black slate is located in the mountain range south of the Panj River. Lake outburst sediments and residual boulders indicate a temporary blockage of the valley followed by sudden drainage, but historical evidence is missing. Ruins of a medieval fortification are situated on an older eastern lobe of the debris (Fig. 5). Detailed interviews in the near village uncovered legends about a "big flood long time ago". Such evidence is certainly purely speculative but can anyway give some indication of former events. More detailed geomorphological work is required in order to better understand this and other prehistoric events.

HISTORICAL LAKE OUTBURST FLOODS IN NORTHERN PAKISTAN

The Hunza and Indus Valleys of northern Pakistan, deeply incised and seismically active (SHRODER, 1998), have a particular history of landslide-dammed lakes (HEWITT, 1982, 1998, 2011) with specific cases in 1841, 1858, 1962, 1974 and 2010.

The largest event is documented from the Indus valley near the Nanga Parbat. In December 1840 or January 1841 a giant earthquake-triggered landslide dammed the Indus River in the vicinity of Raikot Bridge. The exact location of this natural dam is still disputed, but it impounded a temporary lake with a length estimated between 30 (SHRODER, 1998), 57 (DELANEY & EVANS, 2011) and 64 km (MASON,1929). In
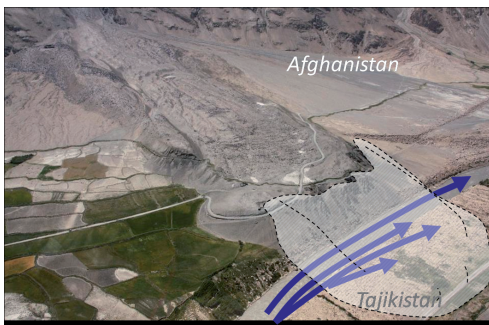

Fig. 5 - Debris avalanche at Dasht-Sulayman upstream Ishkashim in the Wakhan Corridor, Afghanistan. The Panj River eroded the lobe reaching Tajikistan, emptying a temporary lake impounded by the dam. A thin cover of lake sediments exists in the cultivated area on the lower left side and the ruins mentioned in the text are situated on the upper left of the photo. Washed out boulders cover the orographic right side of Panj River as remnants of the lake outburst flood. The eroded cliff on the orographic left side is approx. 50 m high

early June the barrier was overtopped and breached, leading to a tremendous flood wave down the river. The meagre historical records of this huge flood wave were compiled by MASON (1929). Approx. 3-5 billion m³ of water were released in less than 24 hours, 2 million m³ of solids were eroded within a short time. 430 km downstream, the wave front was described as "a wall of water, mud and rocks" which still had a height of approx. 25 m (SHRODER, 1998; NESPAK, 2010). A Sikh army that had camped upstream of Attock was hit by the wave, with at least 500 casualties. The actual volume of water discharged by the Great Indus Flood is unknown and estimates vary similar to those regarding lake length, but MASON (1929) gives dimensions of the barrier that would indicate a volume of more than one cubic kilometre. The release of this volume within one day would indicate an average discharge of over 14,000 m³/s, but the height of the flood wave at Attock suggests an initial discharge several times higher. CORNWELL & HAMIDULLAH (1992) point out that the estimation of the peak discharge varies from 56,630 m³/s (HEWITT, 1964) to 509,000 m³/s (SHRODER *et alii,* 1991). DELANEY AND EVANS (2011) calculated a peak discharge of approx. 114,000 m³/s.

In 1858, another massive slope failure (Ghammessar landslide, 125 million m³) occurred just downstream of Attabad, close to the village of Sulmanabad. Its extensively eroded toe still contains boulders 20–30 m in size (SHRODER, 1998). The landslide blocked the Hunza River and impounded a lake, DELANEY & EVANS (2011) estimate a lake volume of 0.8 km³. In August 1858 the dam was overtopped and the resulting erosion, more than 300 m deep, led to retrogressive slumping of the toe of the landslide – on which the town of Sulmanabad is now located – into the river. MASON (1929) attributes a 20 m flood wave at Attock to the Ghammessar slope failure. According to NESPAK (2010) the flood led to a wave height of 16.5 m at Attock, the flood hydrograph adding up to a volume of 1.85 billion m³. This second Great Indus Flood destroyed several villages and forts downstream of the dam but the population was warned, remembering the 1841 great flood (DELANEY & EVANS, 2011).

Additionally to the Ghammessar slope failure, SHRODER (1998) describe several other slope failures in the proximity of Attabad, for instance the older and the younger Serat slope failures just opposite of the 2010 Attabad landslide (see next chapter). An es-

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timated volume of 1.5 million m³ of the younger Serat landslide was eroded by the river, presumably by an outburst flood. In October 1962 a mass movement was released from the scarp of the Ghammessar landslide, killing six men of the Public Works Department of the Government of Pakistan and impounding water up to Gulmit. When the lake drained suddenly after several months, it undercut remnants of the 1858 landslide, causing several houses of the village of Sulmanabad to drop into the Hunza River. However, they had not been occupied as the population was aware of the instability of that slope. NESPAK (2010) reports of another Hunza River blockage in the area of Gulmit in 1974: this dam failed due to overtopping a few months later, the resulting flood caused some minor damage.

The 2010 Attabad landslide and formation of Hunza Lake, with its far-reaching consequences for the region, is a further entry in the long list of events in that area. It is discussed in detail in the next chapter.

CASE STUDIES OF RECENT EVENTS

Several landslide-dammed lakes have formed in the last 50 years. Examples include the events of Aini (Tajikistan, 1964), Mayunmarca (Peru, 1974), Val Pola (Italy, 1987), Tsatichu (Bhutan, 2003), Hattian Bala (Pakistan, 2005), Tangjiashan (China, 2008), Attabad (Pakistan, 2010) and Siachen-Gayari (Pakistan 2012). Some of these dams have failed. The cases of the failed dam of Hattian Bala as well as of Attabad and Siachen-Gayari where the dams were still intact in March 2013 shall be discussed in detail
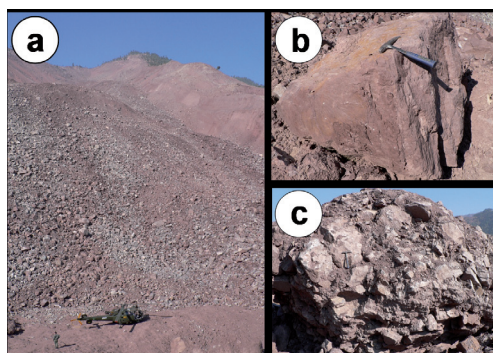

Fig. 6 - *(a) Proximal base of the Hattian Bala rock avalanche, helicopter at the location of the future spillway channel. Karli Lake is situated at the left of the photograph. (b) Sandstone block of the Murree formation in the silt-to claystone landslide debris matrix. (c) Cemented debris of a former landslide at the same location*

CASE STUDY 1: HATTIAN BALA LANDSLIDE

On October 8, 2005, a magnitude 7.6 earthquake struck Kashmir in northern Pakistan and caused many casualties as well as severe damage. Several mass movements were triggered. The Hattian Bala landslide, located at a tributary of Jehlum River southeast of Muzaffarabad (see Fig. 2 for location), was reactivated, resulting in a rock avalanche with a volume of approx. 65 million m³ (DUNNING *et alii*, 2007; SCHNEIDER, 2009; Fig. 6). Consisting of sand-, silt- and mudstones of the Murree Formation, it destroyed a small village and several farms An area of 1.8 km² was directly affected by the landslide, the deposit formed a dam with an area of 0.9 km² impounding Karli and Tung rivers and creating two lakes (Fig. 7a, b). Based on the geometry of the embankment, the maximum volume of the lakes, i.e. when the water level equals the elevation of the lowest saddle of the dam crest, was calculated: Karli (or Zalzal) Lake, the larger of the two, would grow to a volume of approx. 61.7 million m³, Tung (or Bani Hafiz) Lake to 3.6 million m³ (SCHNEIDER, 2009). The portion of the deposit impounding Karli Lake had a maximum depth of 230 m (DUNNING *et alii*, 2007) to 350 m (SCHNEIDER, 2009). Large sandstone blocks were stabilizing the surface of the orographic right (distal) portion of the dam.

After detailed investigations, several measures to mitigate the hazard related to a possible dam failure were initiated (SCHNEIDER, 2009). Besides the installation of a monitoring system and the design of hazard maps and evacuation plans, it was decided to limit the water level of the lakes and to ensure controlled overflow by excavating reinforced spillways for Karli Lake and Tung Lake, with lengths of 425 m and 130 m, respectively. For Karli Lake the spillway was not built not over the saddle, representing the natural drainage path, but over the centre of the dam in order to avoid a destabilization of the adjacent slope. The spillway was partly completed in June 2006, but not reinforced. Its depth was 10 m and the clast size varied from sand to cobbles beneath a relatively thin, coarse bouldery surface layer (DUNNING *et alii*, 2007). The level of Karli Lake reached the spillway at the end of March 2007. In June 2007 the spillway appeared stable, but was not lined. Seepage was observed in the lower, unchanneled section.

Due to the increasing consolidation of the dam, SCHNEIDER (2009) rated the probability of a failure as
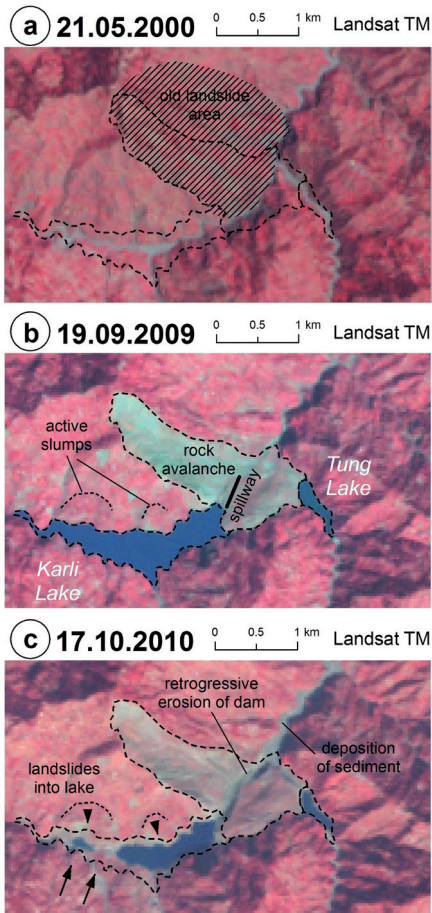
Fig. 7   History of the Hattian Bala landslide and the related lakes: (a) Situation before the landslide. (b) Hattian Bala landslide, Karli Lake and Tung Lake before the breach of the dam. (c) Situation after the breach of the dam with remnants of Karli Lake and Tung Lake

Fig. 8   Eroded breach in the debris deposit of the Hattian Bala landslide below the artificial spillway. Note the landslide scars in the background and the former level of Karli Lake marked by the snow line. Photo taken on February 10, 2010 by Dr. Kausar from the Geological Survey of Pakistan

unlikely if the artificial spillway would be lined with sandstone blocks in order to avoid erosion. However, he also pointed out the scenario of impact waves triggered by the sudden acceleration of active slumps observed on the margins of Karli Lake, especially on the orographic left side (see Fig. 7b).

In February 2010, a process chain including spill over of the dam of Karli Lake and deep retrogressive erosion of the spillway occurred (Fig. 7c and Fig. 8). The following debris flow led to severe damage and one fatality downstream. KONAGAI & SATTAR (2012) conclude that the breach can be attributed to the hydrologic situation (moderate rainfall after dry conditions) in combination with a deteriorating dam body due to. weak weathering resistance of the material. Some landslides observed close to the lake were most likely caused by slope destabilization due to the suddenly lowered lake level and the resulting changes in pore water pressure. However, further investigations are required in order to fully understand the process chain that occurred here.

CASE STUDY 2: ATTABAD DAM

The two Great Indus Floods of 1841 and 1858, as well as smaller events such as GLOFs, increased the awareness of the local population which is generally prepared against natural hazards. The village of Attabad registered cracks and slides over a period of several years. On January 4, 2010 a new 45 million m³ rock slide occurred on the orographic right side of the Hunza gorge, destroying part of the village of Attabad (see Fig. 2 for location). The landslide occurred in a tectonically very active region on a local fault just north of the Main Boundary Thrust and was certainly prepared by seismic destabilization. However, no obvious trigger for the rock slide is evident as the weather preceding the event was cold and dry and no significant seismic activity was measured. The area of western Attabad had been declared a high hazard area for a large-scale failure some years earlier and was therefore evacuated at the time of the event.

At the bottom of the valley, lake sediment presumably originating from the 1858 landslide dam lake was mobilized through undrained loading and possibly through liquefaction of clay, overtopping the rock avalanche deposit and leading to two secondary mudflows (NESPAK, 2010). One of them propagated upstream for a distance of approx. 1.5 km, the other

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travelled 3 km downstream. It hit the settlement of Sarat, claiming 19 lives. 141 houses became uninhabitable (PETLEY *et alii,* 2010).

As a consequence of the Attabad event, a huge debris deposit in the valley blocked the Hunza River. The length of the embankment along the river is approx. 2 km, the width up to 400 m.

As it is the case for most landslide dams, the highest point (210 m above the old valley bottom) is situated at the distal part of the deposit. This is where a large amount of the landslide material accumulated. The saddle is located close to the proximal northern slope of the valley, 126 m above the original riverbed.
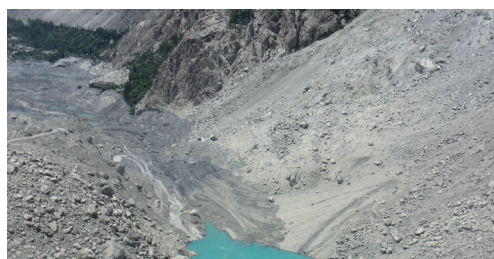

Fig. 9   *Rock slide dam of Attabad, looking W. The rock slide originated from the upper right side of the photograph. The photo was taken on May 26, 2010, a few days before overflow started. Note the erosion channel from seeped water and the boundary between the dark lacustrine deposits and the brighter mass of gneiss rock slide debris*
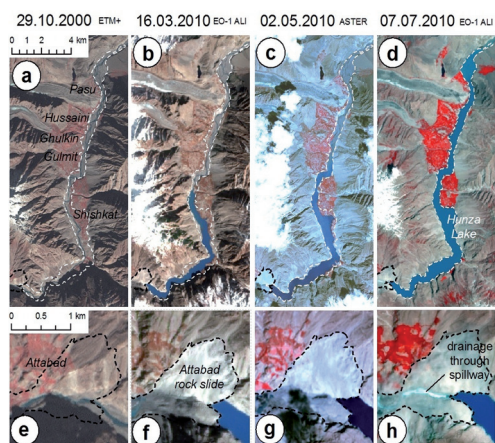

Fig. 10 - *Attabad rock slide and the temporal development of Hunza Lake: (a) and (e) Situation before the Attabad rock slide. (b), (c), (f) and (g) Growth of the lake prior to overflow (d) lake extent after overflow. (h) Situation after overflow with drainage through the spillway. The white dashed line shows the extent of the lake on July 7, 2010, the black dashed line shows the extent of the Attabad rock slide. North is up*

Following the saddle, the slope of the downstream face of the dam is 35° (NESPAK, 2010).

The grain size of the dam material ranges from clay and silt to sand, gravel and large boulders. A large amount of black clay with high organic content was observed in and on the deposit as well as up- and downstream of the dam (remnants of the secondary mudflows). Laboratory tests of the lacustrine sediment mobilized by the landslide showed a plasticity limit of 21-22% and a liquid limit of 28%. The dam is partly covered by an up to 0.5 m thick layer of fine rock powder. The main part of the dam (the actual rock slide deposit) is gneiss, with intrusions of pegmatite and aplite. Whilst finer material dominates the area around the saddle, the coarser material and large boulders have accumulated at the orographic left (distal) side of the dam. The large boulders are not confined to the top of the embankment, but exist also inside the dam, highly contributing to its stability.

Seepage through the dam developed after about 2 months (Fig. 9) and then increased in a nonlinear way. At that point, internal erosion by seepage was considered a potential failure mechanism.

In order to decrease the overall volume of the lake and to regulate the future flow over the dam, the National Disaster Management Authority of Pakistan (NDMA) oversaw the construction of an artificial spillway at the saddle of the embankment. The result was a narrow channel with a bottom width of about 1 m and a depth of 14 m, mainly in the silty clay of the lake deposit.

Figure 10 illustrates the temporal development of Hunza Lake, monitored by the NDMA. Due to the morphology of the valley, which broadens farther upstream of the dam, the filling rate of the lake was initially high and then decreased with time. A slight increase in the filling rate took place in spring 2010 due to snow and glacier melt. In the night of May 28 to May 29, 2010 the dam was overtopped and drained through the constructed spillway. At that point the lake level at the spillway was 111.41 m above the original valley bottom. Overflow increased slowly at first, still allowing for an increase in lake water level of up to 50 cm per day. The spillway underwent retrogressive erosion with almost no basal down cutting. On June 5, inflow and outflow of the lake reached a balance at a lake level of 115.21 m above the original valley bottom. In May 2011, erosion at the outflow of the lake was still

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controlled by large boulders in the dam. Blasting efforts did not significantly alter this situation (Fig. 11).

When overflow started, the lake had reached a length of 21 km and an approximate volume of 450 million m³. In the middle of July 2010, Hunza Lake was about 22 km long, covered an area of 12 km² and had a volume of almost 600 million m³ (KARGEL *et alii*, 2010). The main reason for the further growth of the lake after the onset of the overflow was the higher inflow during summer.

Flooding of the area upstream of the dam led to the inundation of 240 houses in 5 villages. 23 km of the Karakorum Highway were destroyed. 25,000 people living upstream of the dam suffer from lack of economic activity and items of daily sustenance.

CASE STUDY 3: SIACHEN-GAYARI ICE/ROCK AVALANCHE

On 7 April 2011, a snow avalanche from the Saltoro Range hit a northern parent glacier below Bilafond Glacier in the Siachen Region in Jammu Kashmir, Pakistan (see Fig. 2 for location). The resulting ice avalanche entrained material from a lateral moraine and overran the Gayari military camp. 139 people were buried under the deposit of snow, ice, rock and debris
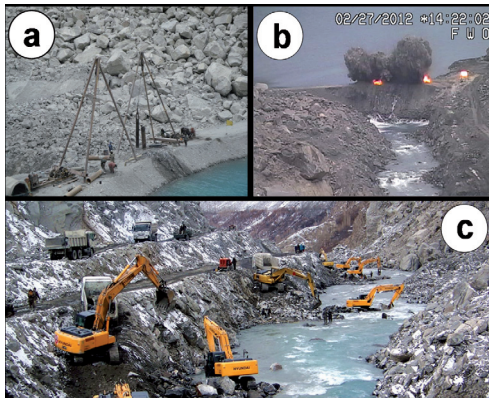

Fig. 11 - Attabad Dam: Front Works Organization (FWO) excavating the overflow channel in order to lower the lake level as well as the hazard of an outburst flood wave. (a) Coffer dam to hold lake water back with drilling rigs for installing explosives. (b) Blasting coffer dam to let the water erode the artificial channel. (c) Excavators working on deepening the channel. The work is slow despite the heavy machinery. It can be done stepwise only during the dry season. Note the large gneiss boulders in a clayey matrix of fine debris mixed with lake sediments, which prevent the channel being eroded. Photos courtesy of FWO

which covered an area of more than 1 km² to a depth of up to sixty metres. Large blocks were embedded in a concrete-like matrix of ice and crushed rock with grain sizes down to silt fraction (Fig. 12, Fig. 13).

Several smaller avalanches from adjacent mountains followed after the main slide. Even though, due to their limited extent, they caused no additional damage, these slides hampered the search operations. The compacted debris cone impounded a lake with a surface area that over time increased to 25 ha. Excavating a drainage channel was necessary in order to reduce the hazard of an outburst flood putting the rescue works as well as the population and infrastructure downstream at risk (Fig. 14). The excavation efforts were successful and an outburst flood was avoided.

Due to a concerted effort by the Pakistani Army seconded by rescue teams from Germany, Norway, and Switzerland, the number of recovered bodies is increasing each day. Around 450 engineers and workers, with heavy equipment, were working around the clock whenever possible. Simultaneous efforts were undertaken to tackle effects of intruding water on site such as the inundation of rescue excavations, erosive cuttings and crevasses. This water was slowing down the pace of rescue efforts.

The Gayari camp was considered a safe place since a 700 years old mosque at the camp site had not been affected by geohazard processes for centuries. However, with global warming, the subsequent

Fig. 12 - Siachen-Gayari ice/rock avalanche, looking NW: the remaining tongue of the glacier, the capped moraine, the ice/rock debris-cone/dam and the beginning of impounding are visible on this photograph. The buried camp is situated on the left side of the picture, where also the spillway was dug out. Photo taken by Pakistan Army shortly after the event

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Fig. 13 - UNOSAT poster used as base for decision making. The avalanche originated in the firn area of the Saltoro Range on the left side of the scene, entraining ice from the seracs and till from the lateral moraine on the orographic right side of the valley. The debris cone/dam and the impounded lake are clearly visible on the post-event scene. Imagery: Ikonos, May 4, 2012

retreat of permafrost and glaciers is putting many settlements and activities in high mountain valleys at risk. Therefore, places formerly deemed safe with regard to natural hazards need to be reinvestigated. A brief look at satellite images of Kashmir showed several hamlets, camps and infrastructures located below possibly hazardous glaciers or rock formations, thus being in situations similar to that which led to the tragedy at the Gayari Camp.

Fig. 14 - Heavy equipment excavating human remains and the artificial spillway. Photo courtesy of ISPR. Note the compacted debris consisting of ice and crushed rocks. Blasting efforts were not successful

CHALLENGES FOR RISK MITIGATION

As demonstrated in the previous chapters, landslide-dammed lakes may drain after a few hours or days, but may also persist for millennia. Even though most dam failures occur in the first few months after their formation, lakes may represent hazards several years later (Karli Lake) or may be at least perceived as such even after 100 years (Lake Sarez). Each stage in the history of a dam requires specific risk mitigation strategies, including a combination of technical and non-technical measures.

Immediate emergency measures have to include the construction of erosion-resistant open spillways or drainage tunnels in order to constrain the lake water level. Such structures reduce upstream flooding and pressure on the dam, allowing for controlled drainage. The finding by SCHUSTER (2006) that some spillways work fine while others fail is supported by the recent cases presented here: the Attabad spillway was still working one and a half years after coming into operation in spite of a rather negative prognosis before. It is often hard to predict the performance of spillways prior to the actual overflow due to a variety of uncer-
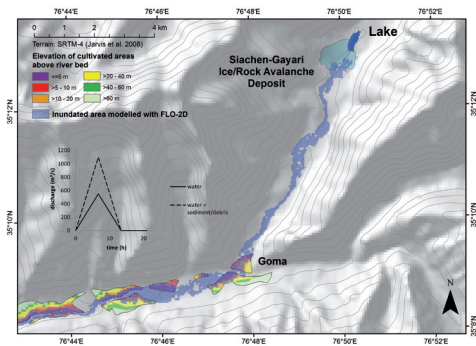
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Fig. 15 - *Hazard indication map showing the area down-stream of the Siachen-Gayari ice/rock avalanche based on heights above river and FLO-2D. The hydrograph applied as input to the modelling of the flood wave propagation considers water bulked with sediment and debris*

Fig. 16   *Example of a hazard indication map for a possible outburst of Hunza Lake covering a section of the valley approx. 80 km downstream of the dam, based on height above river and modelling with FLO-2D. The planes of Gilgit and Danyore are formed by lake sediments of the former Baktor dam (HEWITT, 2011)*

tain parameters, particularly regarding the internal structure of the dam.

Furthermore, well-designed spillways still have a limited capacity and are not able to withstand powerful impact waves triggered by mass movements into lakes. In the case of Hattian Bala, such a wave initiated the retrogressive erosion of the dam because of the absence of rip rap or gabions.

Additional non-technical measures are always required. Such include the evacuation of people from possibly affected zones. NDMA reported that in the case of Attabad, 2,692 families living downstream in the district Hunza and Gilgit were evacuated to 25 camps. Since such action is very sensitive, the extent of the area to be evacuated has to be well defined. A quick method to categorize the susceptibility of downstream areas to inundation due to an outburst flood is to display their height above the river bed. Such a map can easily be derived using GIS and a digital elevation model, but it does not account for the specific characteristics of the possible flood (inundation height, velocity, travel time). Such parameters require the application of physically-based computer models for the propagation of floods and debris flows. Figure 15 shows the hazard indication map for a possible outburst flood of the Siachen-Gayari lake, based on the assumption of outburst hydrographs, subsequent physically-based modelling with FLO-2D and the height above river. Also in the case of Attabad, a combination of height above river and physically-based modelling was applied in order to support the selection of evacuation areas downstream of the dam.
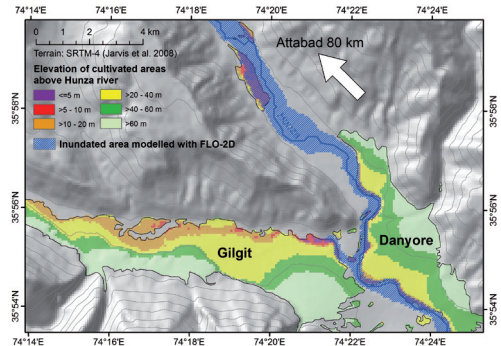
Figure 16 illustrates a section of the resulting hazard indication map, giving a first impression of potentially affected areas. It has to be strongly emphasized that such maps have to be interpreted with utmost care and with the awareness of the specific capacities and shortcomings of the input data applied in the model as well as of the software used. The comparison of the results from more than one type of model is highly advisable.

Flood propagation modelling often simulates worst-case scenarios, assuming a specific initial situation. Long-term evacuation of downstream areas is generally neither desirable nor feasible from a socio-economic point of view, apart from the fact that the population of evacuation camps yearns to return to their houses. Therefore the prediction and early recognition of specific critical situations is essential, particularly in the case of dams persisting for more than a few weeks or months. However, such tasks have proven to be difficult. Continuous monitoring of possible triggers of dam failures (e.g., unstable slopes or inflow into the lake) in combination with the installation of sensors for impact waves and flooding may be highly useful given that (1) the systems are maintained in an appropriate way, (2) they are connected to an operational emergency warning system and (3) the communities downstream are prepared and know how to react in case. Computer models can help to estimate travel times and therefore the period available for evacuation.

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CONCLUSIONS

Landslides are common geomorphologic processes in mountain areas all around the world. Sometimes they block entire valleys and impound lakes which may drain suddenly. Steep and narrow valleys in seismically active zones (like the Pamir of Tajikistan and the Karakoram in Northern Pakistan) are particularly susceptible as geomorphologic and historical evidence has shown along with more recent cases.

Even though there are no means to prevent the formation of landslide dams, the prediction of possible dam failures remains a challenge. Adverse effects on people, property and infrastructures can be alleviated by applying a combination of appropriate risk mitigation strategies, including monitoring, awareness and preparedness building. Using the know-how from former events helps to understand these actual rapid landform change processes.

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