Non-seismic landslide hazards along the Himalayan Arc

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ABSTRACT: Asia is the most landslide-prone continent of the terrestrial surface of the Earth, and the southern edge of the Himalayan Arc represents a particular hotspot within this wider area. In this paper an analysis is made of the occurrence and impact of non-seismic landslides within the Himalayan Arc, using the Durham Fatal landslide database as the primary source. It is shown that the occurrence of fatal landslides in time and space is heavily influenced by the confluence of high rates of tectonic processes, the occurrence of monsoon rainfall and the presence of a vulnerable population. In the second part of the paper an example of an acute landslide hazard in the Himalayan region is presented. The 4th January 2010 landslide at Attabad in Gilgit-Baltistan, N. Pakistan, blocked the Hunza river to a height of about 120 m. Over the next five months a lake with a total volume of over 450 million m^3 developed, drowning farmland and houses, blocking the Karakoram Highway and isolating about 25,000 people on the north side of the blockage. The paper presents data on the development of both the lake and of seepage through the dam, and on the way in which flow developed during the overtopping event. At the time of writing the lake was still present in the landscape, generating a substantive hazard to downstream communities and representing a huge management problem for the National Disaster Management Agency.

1 INTRODUCTION

1.1 *Landslides and fatalities*

The ultimate cost of landslides to human societies is loss of life. Unfortunately the resilience of humans to landslides is poor, as burial to even relatively shallow depths cannot be survived without a supporting structure. Studies suggest that burial in approximately 30 cm of sand generates sufficient force to overwhelm respiratory and diaphragmatic capacity (Zarroug et al. 2004). Even where victims of burial have been recovered alive, rapid, high-level treatment such as intubation is usually required to ensure survival. Of course asphyxiation is not the only cause of morbidity in landslides. Sanchez et al. (2009) found that of the 42 fatalities caused by debris flows on the island of Chuuk in Micronesia in July 2002, 92.9% (n=39) were the result of asphyxiation, 7.1% (n=3) of blunt trauma injuries to the head, and 2.4% (n=1) of blunt trauma injuries to the abdomen. These proportions of fatalities are in line with expected levels extrapolated from avalanche morbidity, for which there are far better data. For example, McIntosh et al. (2007) found that of 56 avalanche deaths in Utah, 85.7% were the result of asphyxiation, 8.9% were caused by a combination of asphyxiation and trauma, and 5.4% were due to trauma alone. Head injuries were reported to be frequent in those killed only by trauma. Thus, the causes of loss of life recorded at Chuuk may be considered to be typical for landslides, although in some cases drowning may also occur, and the proportions may differ in more energetic events, such as rockfalls and rockslides.

Overall, there is a remarkable and perhaps somewhat surprising lack of research into the nature and causes of mortalities in landslides, and indeed of the spatio-temporal distribution of landslide fatalities. This paper addresses in part one of these issues, providing a review of the distribution in time and space of rainfall-triggered landslides causing loss of life, with a focus on the Himalayan Arc. The aims of the first part of the study presented here are to: 1. quantify loss of life in landslides within this region, and to understand this in a global context; 2. determine the distribution of fatalities in time and space; and 3. examine the climatic triggers of landslides that induce fatalities. The study makes use of the Durham Fatal Landslide Database (DFLD), which has collated information on the loss of life in landslides on a global basis since September 2002.

In the second part of the paper an example of an acute landslide hazard is examined, in this case the

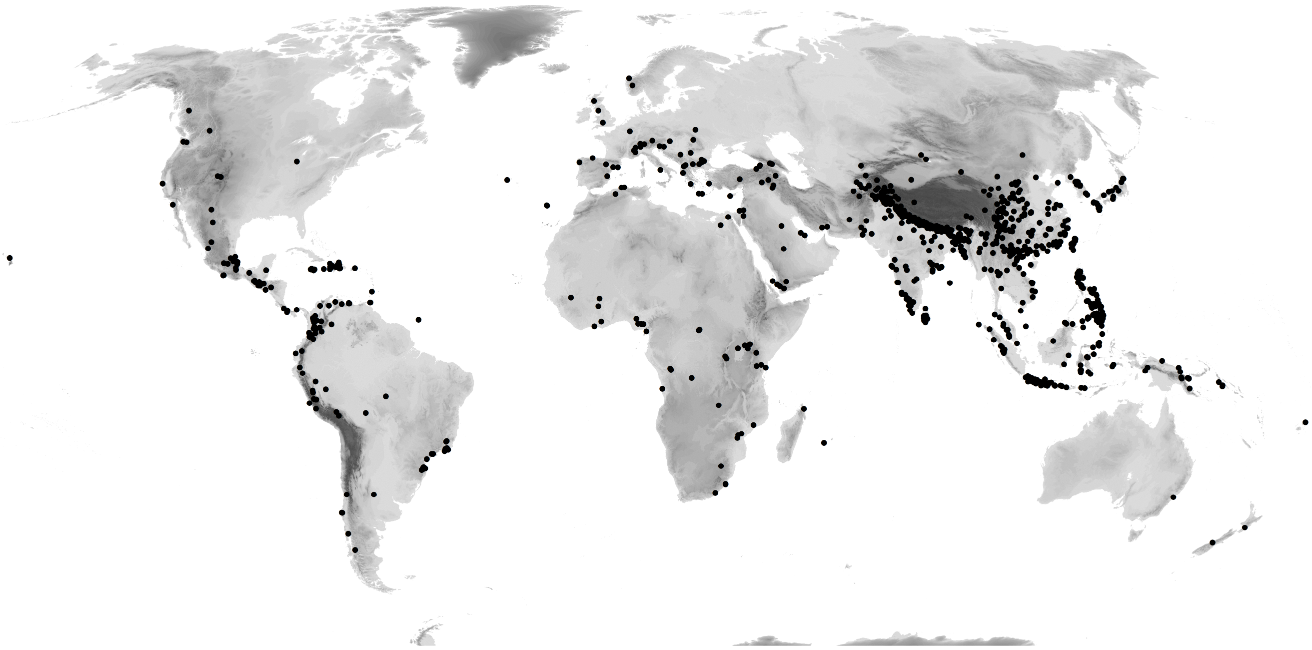

Figure 1: Recorded NFLs worldwide between 1st January 2006 and 31st December 2009. Each dot represents a single NFL. The background image is a digital elevation model for which dark tones represent terrain with a high elevation.

crisis-inducing 4th January 2010 valley-blocking landslide at Attabad in Hunza, N. Pakistan.

1.2 *The Durham Fatal Landslide Database*

The DFLD represents an attempt to collate reliable data on the occurrence of landslides that cause loss of life. Global data are collected on a daily basis using a combination of online searches, analyses of government data, reviews of the technical and scientific literature and through direct reports from correspondents. Data are only collected for landslides that cause loss of life. For each landslide information is recorded on the date of occurrence, the location, the landslide type, the trigger, the number of fatalities and the number of people injured. In addition the database includes a free-text section that allows other details of the slide to be recorded where they are available. All mass movements are included, but floods and snow / ice avalanches are excluded. Strenuous efforts are made to validate the resulting dataset, and records are corrected where more data become available, even where this is a long time after the event.

The reliability of the database is discussed in several previous publications (Petley et al. 2005; Petley et al. 2007; Petley et al. 2008) but in brief such databases can be shown to provide a good overview of the hazards, though with quite large error bars (Downton and Pielke 2005 for example). Most such databases underestimate the true hazard as result of under-reporting of smaller events (i.e. in this case those with a small number of fatalities) and those that happen in very remote locations.

The concept behind such a data collection exercise requires recognition of two key aspects. First, fatalities represent the only indicator of loss that is both universal and practicable. Other indicators, such as economic loss, have a variable value around the world, or even within countries, rendering comparison between areas essentially impossible. Attempts to correct economic value according to an economic indicator such as per capita GDP have proven to be unsatisfactory (Downton and Pielke 2005). On the other hand, an indicator such as the number of landslides occurring is universal, but essentially impossible to collate across even small areas of terrain. Fatalities on the other hand are a "universal currency" in that life holds the same essential value in every environment. Thus, fatalities allow comparison of trends and distributions in both space and time (Dao and Peduzzi 2003).

The second factor has been the extraordinary growth of global connectivity associated with the development of internet-based communication. In particular, the availability of web-based news coverage has meant that reports of local events are now available globally, especially when searched using news aggregator tools. Landslides that result in even a single fatality are generally reported in the local press at least, and these reports are then widely available via news aggregators. Thus, a systematic analysis allows a reasonable estimate of the impact of landslides in terms of fatalities to be gained.

2 FATAL LANDSLIDES ALONG THE HIMALAYAN ARC

2.1 *Context – the Global landslide distribution*

As of 28th May 2010, the DFLD has records for a total of 2,836 fatal landslide events, causing 78,354

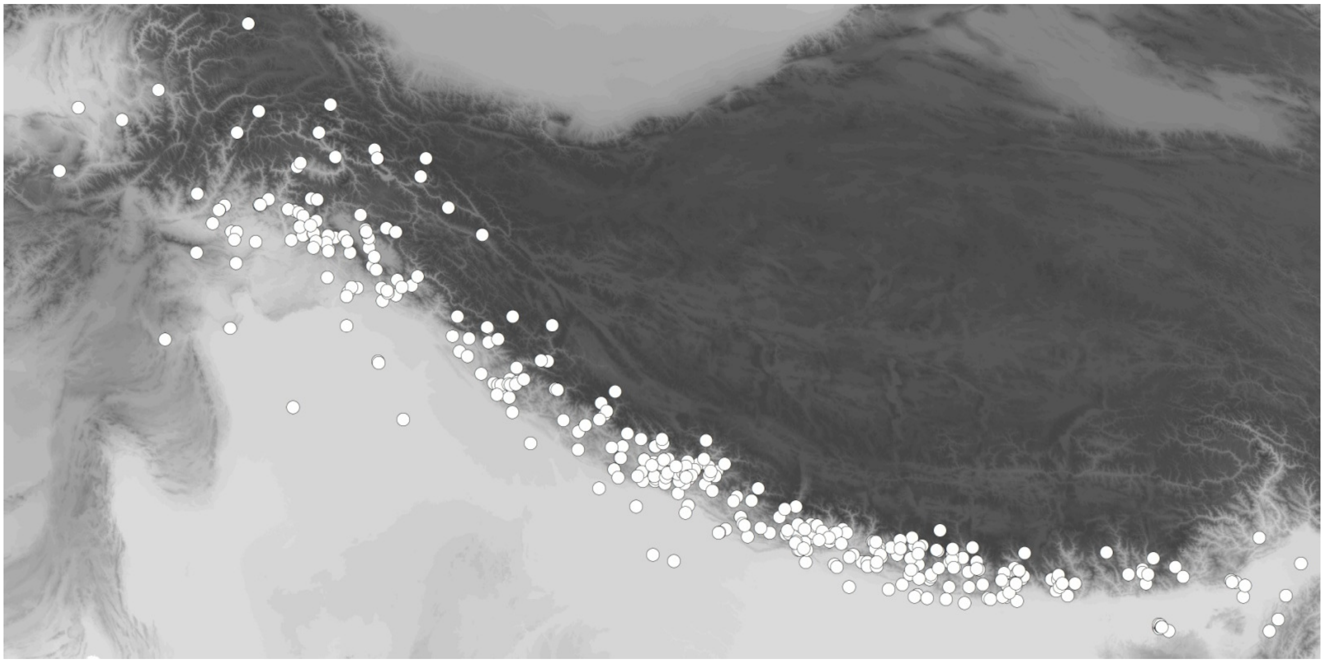

Figure 2: Recorded NFLs within the study area between 1st January 2004 and 31st December 2009. Each dot represents a single NFL. The background image is a digital elevation model for which dark tones represent terrain with a high elevation.

recorded fatalities. Of these, 2177 landslides and 75,958 fatalities occurred in the six year period covered by this paper (1st January 2004 to 31st December 2009). The fatality count is dominated by the landslides associated with two large seismic events in Asia – the 2005 Kashmir earthquake in Pakistan and India (26,400 fatalities, Petley et al. 2006) and the 2008 Wenchuan earthquake in China (approximately 20,000 fatalities, Yin *et al.* 2009). However, seismically-induced landslides are beyond the scope of this paper, which concentrates on non-seismic fatal landslides (NFL's).

The spatial distribution of the recorded NFLs is shown in Fig. 1, where each dot represents a single NFL. The spatial distribution of the NFLs is very uneven, with hotspots in a number of key locations, most notably in Asia. The Himalayan Arc is clearly the most substantive hotspot, with a recorded occurrence of NFLs along the entire length of the southern edge of the mountain chain, but not extending northwards onto the Tibetan plateau. It is this globally-important NFL hotspot that is the subject of this paper.

2.2 *Aggregate statistics for the Himalayan Arc*

In the period between 1st January 2004 and 31st December 2009 a total of 402 individual NFLs were recorded in the Himalayan Arc region, representing a mean of 67 events per annum. In total these NFL's killed 2,252 people, representing a mean of c.375 deaths per annum. In comparison, landslides associated with the 2005 Kashmir earthquake, which affected the area within the West Himalayan syntaxis (i.e. the western margin of the Himalayan Arc), is believed to have killed about 26,400 people, with a single slide, at Hattian Bala, leading to about 650 fatalities (Petley *et al.* 2006). Thus, over the timescale of this study, seismically-induced landslides cause a greater loss of life than do non-seismic events, even though the temporal frequency of occurrence is much lower. Given the large seismic gaps along the Himalayan front, and in particular in west Nepal, this is a concern in terms of future landslide occurrence in this region.

The distribution of the NFLs within the study area is shown in Fig. 2, for which the base image is an SRTM global digital elevation model. The NFL distribution is heavily focused on the southern edge of the mountain chain, not in the areas of the highest terrain or indeed of the steepest slopes. In the west NFLs extend northwards from the main southern edge of the mountain chain, picking out the major river valleys of the Indus, which are quite densely populated. This northward extension of the landslides is not observed at the east end of the mountain chain.

The observed distribution reflects a number of factors simultaneously:

- The zone with sufficient relative relief (note not altitude) that landslides can occur;
- The zone with a sufficiently high population density that high energy landslides can interact with people;
- The zone with seismic activity (movement on faults) that both destabilises slopes and creates terrain;
- The zone with sufficient rainfall occurrence that landslide triggering can occur.

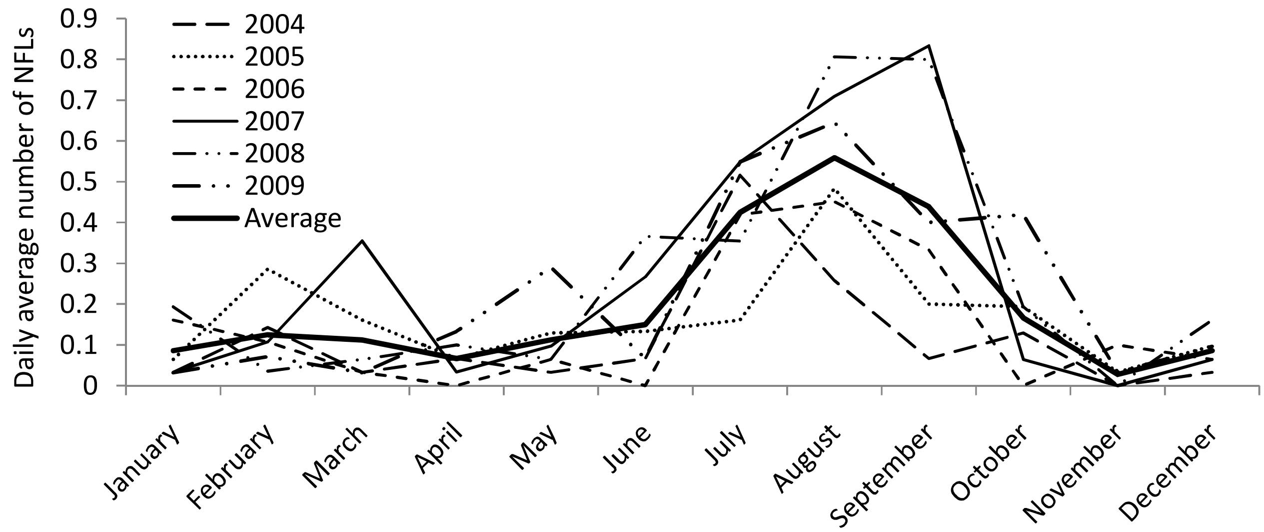

Figure 3: The monthly occurrence of NFLs by year, including the overall average occurrence. Note that the data are displayed as a daily average rate to allow for the different number of days between months.

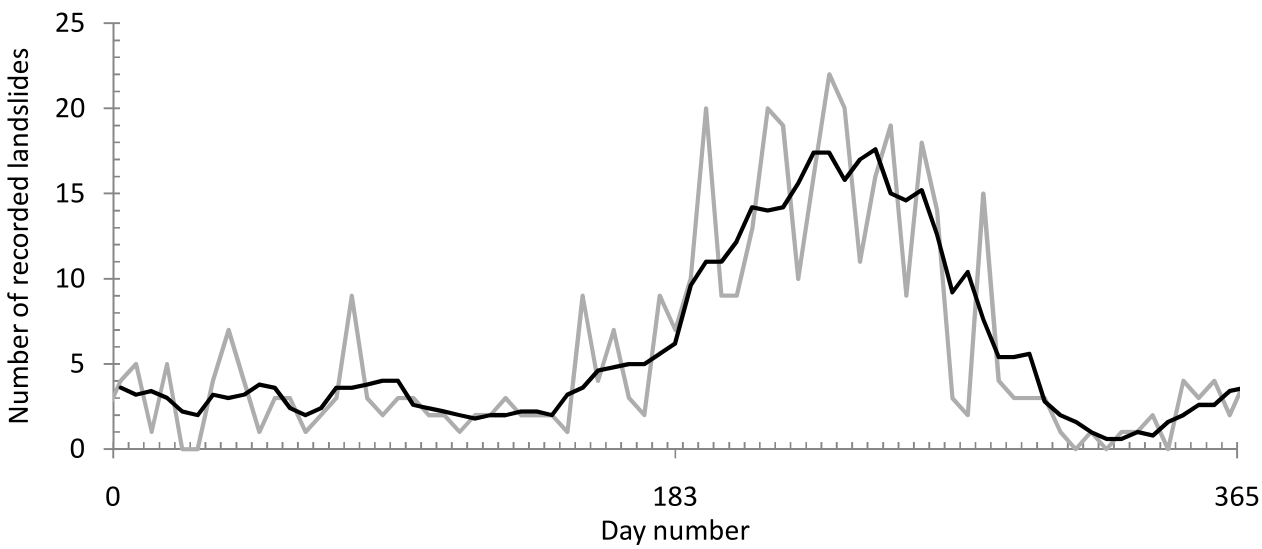

Figure 4: The total number of NFLs in five day bins through the year. The light coloured line is the total number of recorded NFLs, the darker line is the 25 day running mean to show the overall trend.

This confluence of factors is only observed along the southern edge of the mountain chain. Of course the vulnerability / (lack of) resilience of the population is also important, but as levels of poverty are high throughout this region, this is unlikely to be a significant factor in determining the relative distribution, even though it is key in determining the number and impact of NFLs.

Fig. 3 shows the monthly occurrence of NFLs by month and year. There is considerable variability in the annual pattern, but the average line shows the overall trend very clearly, which is low occurrence between of NFLs between January and May, but then substantially elevated occurrence in the period June to October, returning to the background rate in November. The peak occurrence occurs in August, and the minimum in November.

This trend is better illustrated using the whole

shows the intense peak in occurrence at around days 230 to 250 (August), and the minimum at around day 320 (November). It is interesting to note that when displayed in this way the peak period occurrence is asymmetric, with a less steep rising limb and a steeper falling limb, and that the period of lowest landslide occurrence is just after the peak period.

The observed pattern closely corresponds to the occurrence of the Southwest monsoon, which drives the landslide occurrence through its control on precipitation. In this northerly area of South Asia the SW monsoon typically extends up to the Himalayas in late June or early July, and begins to retreat in early September. The SW monsoon is responsible for >80% of the precipitation across the Himalayan region.

There is no clear trend in the annual occurrence the time span covered is probably too short to show such anything other than a monotonic trend. It is clear that there is considerable inter-annual variability in both the occurrence of NFLs, and in their impact in terms of lives lost.

The statistical distribution of the size of the landslides in terms of the number fatalities caused by

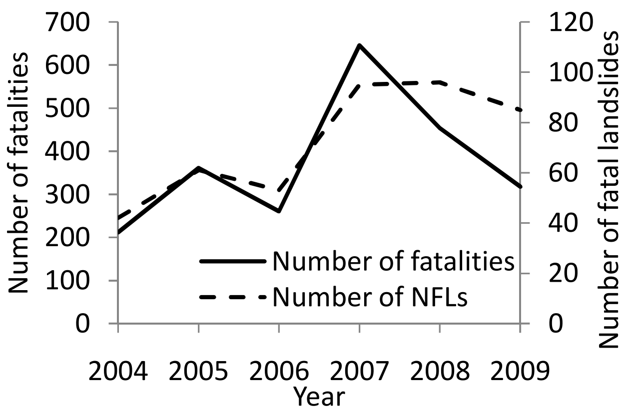

Figure 5: The number of NFL's (right hand axis) and of resulting fatalities (left hand axis) by year in the study area

each event shows a power law distribution (Fig. 6), with the same "roll-over" for the smaller events identified for landslide area and volume datasets (Guzetti et al. 2002). In this case the roll-over is probably partially a consequence of under-sampling of smaller NFLs (small events in remote areas are probably inadequately reported), but it probably also

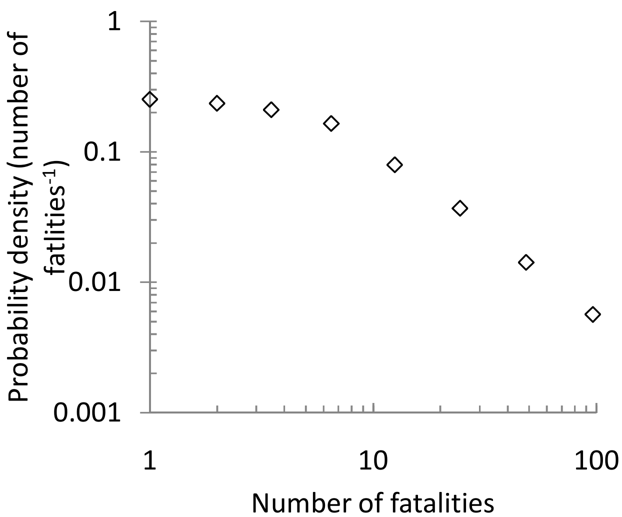

Figure 6: The probability density function for landslide size, as indicated by number of fatalities.

reflects the roll-over seen in the landslide magnitude datasets.

In the remainder of this paper a case study will be presented of a large landslide hazard in the Himalayan chain – the Attabad landslide in Hunza, N. Pakistan.

3 THE ATTABAD LANDSLIDE, HUNZA, PAKISTAN

3.1 *Background – the Attabad landslide event*

On 4th January 2010 a very large landslide occurred at the village of Attabad in Hunza, Northern Pakistan (36.307ºN, 74.816ºE) (Fig. 7). The slide occurred from the northern wall of the Hunza river valley, when a mass of about 45 million cubic metres detached from the wall and traveled up to about 1175 m vertically and 1,300 metres horizontally. This mass blocked the valley across its entire width to a depth of between 120 m (at the saddle) and 200 m at the highest point on the landslide mass (Fig. 8). The slide appears to have been complex, with eyewitness reports suggesting that there were a series of detachment events. The floor of the river valley consisted of river bed and terrace gravels overlying a lacustrine silty-clay deposit that had been laid down in the bed of a lake formed by a landslide in 1858 at Salmanabad, about 3 km downstream. The main body of the Attabad landslide was dynamically emplaced on top of this deposit, which was mobilized by the impact (Fig. 8). Part of the silty-clay formed a mudflow that travelled about 1.5 km upstream. Another portion was squeezed against the valley wall to the south, and was then deposited on top of the saddle of the Attabad landslide. The remainder of the deposit was mobilized to form a mudflow that travelled at high speed for a distance of about 3 km downstream. In the path was the small hamlet of Sarat, located close to the river on the floor of the valley. Nineteen people were killed at this location,

Figure 7: An oblique aerial image of the Attabad landslide from the upstream side (image courtesy of Nusrat Nasab / Focus). The source of the landslide is on the right side of the image. Note the thin band of dark lacustrine deposit between the landslide mass and the valley wall on the left side of the image. The debris is piled on this side of the valley, indicating a high speed flow. Note the lowest point on the right side of the deposit. The spillway was constructed in this part of the landslide deposit.

representing the only fatalities from the landslide. However, 141 houses, providing the homes of 1,652 people, were destroyed or rendered unsafe.

The main rock avalanche deposit in the valley was about 1.5 km long and 300 m wide. The deposit was asymmetric, with a steep upstream face but a lower gradient downstream side due to the presence of the mudflow, which was overlain on the rockslide debris. The saddle of the deposit was located on the side of the valley nearest of the source; the debris was banked up on the far side of the valley, suggesting a high speed of emplacement (Fig. 7).

The landslide created a natural dam that blocked the Hunza River, a major tributary of the Indus. The Hunza Valley also contains the important Karakoram Highway, a major strategic route that links Pakistan and China, although at the time of occurrence the highest section of the road were closed by the winter snow. The loss of the road left 25,000 people living to the north of the landslide isolated, causing considerable hardship. These people lost a key source of income – trade along the road, which has proven to be economically disastrous – and access to basic needs such as health care and electricity was prevented. The only viable transportation was via a boat service, which became increasingly problematic as the length of the lake increased. The maximum length of the lake was >21 km.

There was no obvious trigger for the landslide. The weather conditions were dry and cold, but not exceptionally so, and there was no recorded seismic event of sufficient magnitude to induce collapse. Thus, it appears that this was probably a time-dependent failure. Eye-witness reports suggest that precursory rockfalls, as per Rosser et al. (2008), were observed prior to the collapse, supporting the time-dependent hypothesis. The site had been identified as being at risk of a large-scale failure some years earlier by geologists from Focus Humanitarian Assistance due to the presence of large tension cracks extending across the slope (Hughes 2003). For this reason the village of Attabad had been evacuated and relocated, with the move being enabled and facilitated by Focus. In consequence, no fatalities were recorded in Attabad itself, despite the extensive loss of houses. The secondary flow, which caused the loss of life in Sarat, could not have been foreseen.

The slide occurred on a steep cliff consisting primarily of diorite and granodiorite of the Cretaceous-Tertiary age Karakoram batholiths. These rocks contain pervasive veins of pegmatite and quartz and are heavily tectonised, with both folding and large- to local-scale faulting being evident. The slope was extensively mantled with glacial tills and colluviums, which were integrated into the slide. The surrounding landscape is characterised by landslide scars and deposits. Most of these are unmapped, but a review of some of the slides, including a number of ancient landslides at Attabad, is provided in Shroder (1998).

3.2 *The Attabad lake*

Immediately after the landslide occurred, a lake started to develop on the upstream side of the mass. From an early stage this lake was monitored by the geological team from Focus. The graph of water level and filling rate against time is shown in Fig. 8. As expected the filling rate was initially high and declined with time. In the latter stages the rate of water level rise increased slightly – this was due to increased river discharge associated with snowmelt and release of water from the local glaciers. Overtopping was achieved on the night of 28th-29th May

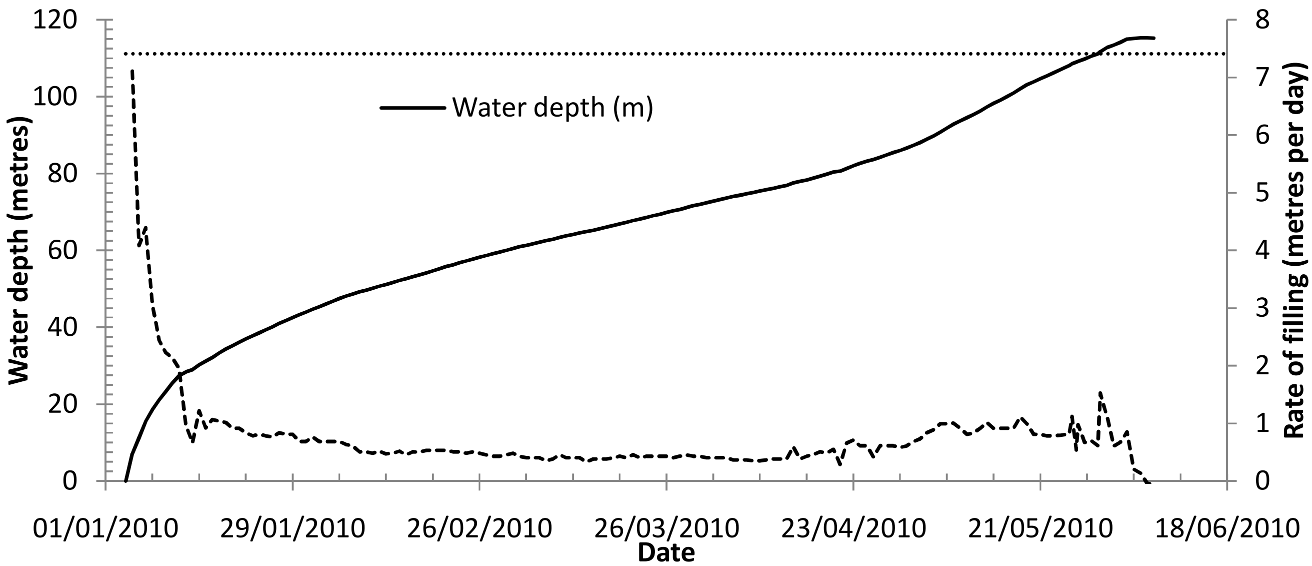

Figure 8: The trend in lake level with time as measured by the Focus geologists. The dotted line represents the height of the base of the spillway at the point of overtopping. The Dashed line shows the rate of rise of water level. Note the seasonally-driven increase in filling rate in the final stages, caused by increased river flow associated with melting of snow and glacial ice.

2010 when the water level reached the lowest point on the saddle. This point was located in a narrow spillway channel, approximately 14 m deep, excavated into the silty-clay at the saddle of the dam. At the time of overtopping this spillway was about 1 m wide at the base and was unlined.

Forecasting the time of overtopping proved to be very difficult for three reasons:

1. The Hunza River has a very strongly seasonal discharge, such that the rate of inflow of water was expected to increase substantially in the Spring. Although some increase did occur, this was less than had been anticipated, such that the overtopping event was delayed.
2. Good quality topographic data were not available, meaning that determining the potential storage volume proved to be very challenging. Various iterations of DEMs generated from SRTM and ASTER data were tested; neither approach proved to be very satisfactory;
3. The base of the spillway underwent heave as the lake level rose, possibly in response to either increased saturation of the silt and/or creep of the channel wall materials. Some of this creep may have occurred in response to their having been loaded with materials excavated from the channel.

To mitigate uncertainty in terms of the overtopping date, daily graphs were produced and posted online on a dedicated website by the combined Focus and Durham team, showing the freeboard reduction with time, and a commentary was provided to explain how and why this was changing. These graphs were produced in reaction to growing disquiet in Pakistan that the responsible government body, the National Disaster Management Agency (NDMA), was providing unreliable information. In particular, on a number of occasions NDMA personnel were quoted as forecasting imminent overtopping, even when the water level was several tens of metres below the spillway. The graphs generated by the Focus and Durham team were widely used in Pakistan, and provided an independent source of information to planners, NGOs and potential victims of a flood.

At the time of overtopping the lake had reached a length of about 21 km, and an estimated volume of about 450 x 10^6 m^3 of water. The lake flooded a number of villages and destroyed 171 houses. It also destroyed 23 km section of the Karakoram Highway, including a number of bridges, and one that was under construction, and further isolated the communities upstream. All communications with the upstream areas required the use of boats that travelled from the upstream side of the landslide. Thus, to travel into the isolated area required transportation on foot or by 4x4 over the top of the landslide and then the use of the boat service. Unfortunately, throughout the crisis rockfalls continued to occur from the scar of the Attabad slide; one person was killed and another seriously injured by one of the larger rockfall events.

3.3 *Seepage*

Early in the crisis seepage was identified as a potential mode of failure for the dam, although the morphology of the dam and the presence of the lacustrine deposit reduced the chances of this type of collapse. In the initial stages of filling no seepage was observed, but seepage developed about two months after landslide emplacement, and then steadily increased with time as the lake filled (Fig. 9). Seepage progressively developed in six locations on the downstream face of the dam, with the rate of

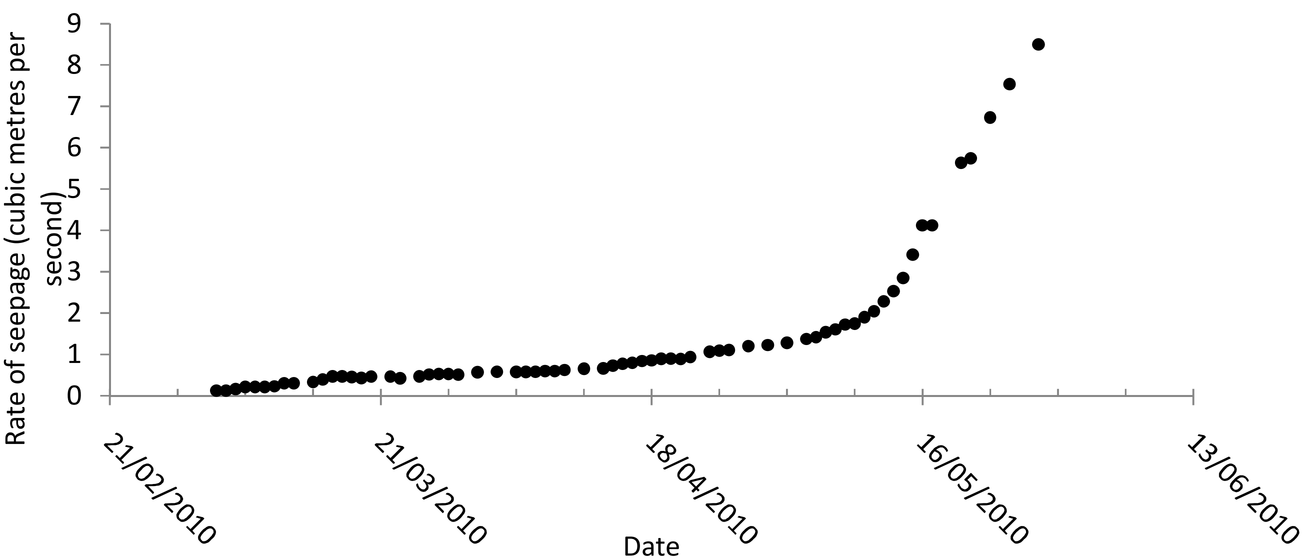

Figure 9: The measured total seepage rate through the landslide dam. Seepage measurements were halted at the end of May 2010 for safety reasons.

flow increasing non-linearly with time (Fig. 9). Whilst for a time the rapid increase in the seepage rate caused concern, it did not induce failure of the dam prior to overtopping as had been feared.

3.4 *Post overtopping behaviour*

Overtopping occurred on the night of 28th-29th May 2010 at an elevation of 111.41 metres above the valley floor. Water flow through the spillway increased slowly at first, during which time the lake level continued to increase at more than 50 cm per day. The channel suffered substantial, rapid retrogressive erosion rather than basal down-cutting, over a period of about six days until the outflow equilibrated with inflow on 5th June 2010 at 04:00 local time, by which time the lake level had risen by a further 3.81 m to give a final depth of 115.21 metres (fig. 9). Headward erosion was controlled at the saddle by the presence of a large boulder, which prevented the initiation of an initial outburst event (Fig. 12). At the time of writing (9th June 2010) the lake level had stabilized and slow downcutting of the channel appeared to be occurring, although flow was still be strongly controlled by the presence of a single large boulder in the channel at the saddle. The short to medium term prognosis for the dam was unclear, but the potential for a sudden outburst event remained, posing a management problem for the government. The highly seasonal flow regime of the Hunza suggests that the peak summer flow might be expected to occur in late July or in August, with an average monthly discharge more than double that of June, and a peak flow about 50% higher again. Thus, it is likely that the integrity of the dam will again be threatened at this time. Meanwhile, with thousands of people displaced from their land, the management issues are formidable, with considerable pressure within Pakistan to blast the barrier. Clearly, such an action requires rigorous analysis first; it is not clear how this analysis would be undertaken.

4 CONCLUSIONS

In this paper an analysis is presented of the temporal and spatial occurrence of NFL's in one of the most landslide-prone regions on earth. It is shown that the spatial and temporal distribution of the landslides can be related to the key parameters associated with landslide causation. No overall trend in NFL occurrence is noted, with inter-annual variations probably reflecting the dynamics of the monsoon. In the second part of the paper, an initial analysis is presented of the Attabad landslide in Hunza, N. Pakistan. This example serves to demonstrate the extreme difficulty of managing landslide hazards along the Himalayan Arc. At the time of writing the final outcome of this landslide disaster is unknown, but it has already affected thousands of lives and disrupted development activities across a wide area.

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