Landslides and sustainable development: managing the cost of landslides in less developed countries

D.N. Petley

Department of Geography, University of Sheffield, Western Bank, Sheffield, S10 2TN, United Kingdom

Email: d.n.petley@sheffield.ac.uk

Abstract

Landslides continue to inflict major costs on society worldwide, in terms of economic losses; human mortality and morbidity; and environmental damage. Over the last two decades there have been substantial advances in our understanding of slopes and of their behaviour when stable and when unstable. However, at present this is not translating into a reduction in levels of loss; indeed in some circumstances there is evidence that damage caused by landslides is accelerating.

The reasons behand these patterns are complex, and include climate change (and in particular increases in peak rainfall intensity); loss of forest and other natural habitats; increasing wildfire occurrence; and enhanced levels of development on marginal terrain. However, most of the losses of human life occur in less developed countries, especially in Asia and Latin America, such that these are the areas in which attention will need to be focused if losses are to be reduced.

One key element of the high levels of loss in less developed countries is mining. Evidence from the fatal landslide database suggests that landslide losses from mining activities are increasing with time, especially in South Asia. This appears to be associated with poor mining practices and with a lack of regulation – most of the landslide losses from mining occur in unregulated mines, or in locations in which artisanal mining is being undertaken. However, landslides are also a significant problem in better regulated mines too. This paper examines in particular the behaviour of tailings landslides, in which there is an unacceptably high level of failure at present. It is shown that post-failure many tailings landslides show exceptional mobility, considerably more than that shown by most other landslides, greatly increasing their impact. The paper also examines the landslide record of one less developed country – Nepal – demonstrating that despite the improvements in landslide understanding, losses continue with no sign of a reduction. The paper considers those elements needed to put in place a national programme of slope management. Sadly, the requirements are quite demanding, meaning that losses will continue to mount in most poor countries.

1 INTRODUCTION

Landslides inflict a high cost on society in terms of human mortality and morbidity; economic losses and damage to the environment (Petley 2012). Whilst landslides are a suite of natural processes that are an essential part of the dynamic evolution of most landscapes, humans serve to change the temporal and spatial distribution of landslides, and there magnitude, in multiple ways (Alcantara-Ayal 2002). In some cases this is through the prevention or control of landslides that would otherwise occur naturally, in order to protect vulnerable assets. In most cases however this is through an increase in the occurrence of landslides; there is a huge volume of documented case study material that demonstrates this increase both in modern and in historic societies (for example Glade 2003; Shu *et al.* 2019).

The greatest impact of landslides in terms of lives occurs in less developed countries, most notably in Asia and in Latin America (Petley 2012; Froude and Petley 2018). Whilst there is less robust evidence to support this hypothesis, it is also likely that the greatest contemporary impacts in terms of environmental degradation and percentage of GDP lost also occur in less developed countries. This may not have been the case in the past. There is also evidence that these impacts are increasing with time, in part because of changes of land use in hilly terrain and in part because of the effects of global heating, including changes in patterns of vegetation, increasing wildfire occurrence and increasing peak precipitation intensities (Gariano and Guzzetti 2016). Despite improved understanding of landslide processes and causation, we continue to lose the battle.

This paper considers the patterns of loss associated with landslides on a global basis, and then focuses on less developed countries. I have chosen to examine one particular aspect of landslides in poorer countries, those caused by mining operations. These events are an important part of the total landslide burden, but they are poorly considered in the literature from a global cost perspective. From there I revisit the cost of landslides in one of the countries that suffers the highest level of loss – Nepal – and consider why it is that we have made so little progress in loss reduction in such places.

2 LOSSES IN LANDSLIDES IN LESS DEVELOPED COUNTRIES

Petley (2012) and Froude and Petley (2018) both highlighted the high burden of landslides in less developed countries. The basis for these analyses has been the global database on landslide fatalities, maintained by the author since September 2002; the data continue to be collected and collated today. The basis of this dataset is extensively described elsewhere; it collates information on landslides that lead to a loss of life on a global basis, using a variety of sources. Analyses of the database are available in Petley (2012) and Froude and Petley (2018), and a comparison between the database and a separately-compiled regional dataset collected for Latin America was published in Sepulveda and Petley (2015). Alignment between the two datasets was found to be high. We usually undertake detailed analysis of the dataset from 1 January 2004 as the data are considered to be robust and consistent from this point onwards (Petley 2012). This study draws upon the same dataset, but extends the analysis from 1 January 2014 to 31 December 2017 inclusive (and to December 2018 in the case of Nepal).

Figure 1 shows the cumulative number of fatal landslides in the dataset, divided by continental area, whilst Table 1 provides the total number of fatal landslides and the number of resulting fatalities for each region. Four regions dominate the data – S. Asia, SE. Asia, E. Asia and S. America. The other regions, represented by the other data lines on Figure 1, are comparatively insignificant compared with those four key regions. Froude and Petley (2018) noted that in all these four of these regions there is significant number of less developed countries, although the influence is variable. Thus, for example, South Asia has a number of very low income countries (e.g. Nepal, Bhutan and Bangladesh), whilst East Asia has fewer. Of course, poverty is not the only determinant of vulnerability to landslides – many countries in Africa have very low income levels but do not generate comparatively large numbers of fatal landslides, reflecting the need for both a landslide prone terrain and significant triggering events. Thus, there is strong evidence that landslides that induce loss of life are strongly associated with less developed countries in which there is a combination of some or all of inadequate control of planning processes, poor construction techniques, rapid land use change in upland areas, inappropriate maintenance, an inadequate response to the development of instability, high vulnerability

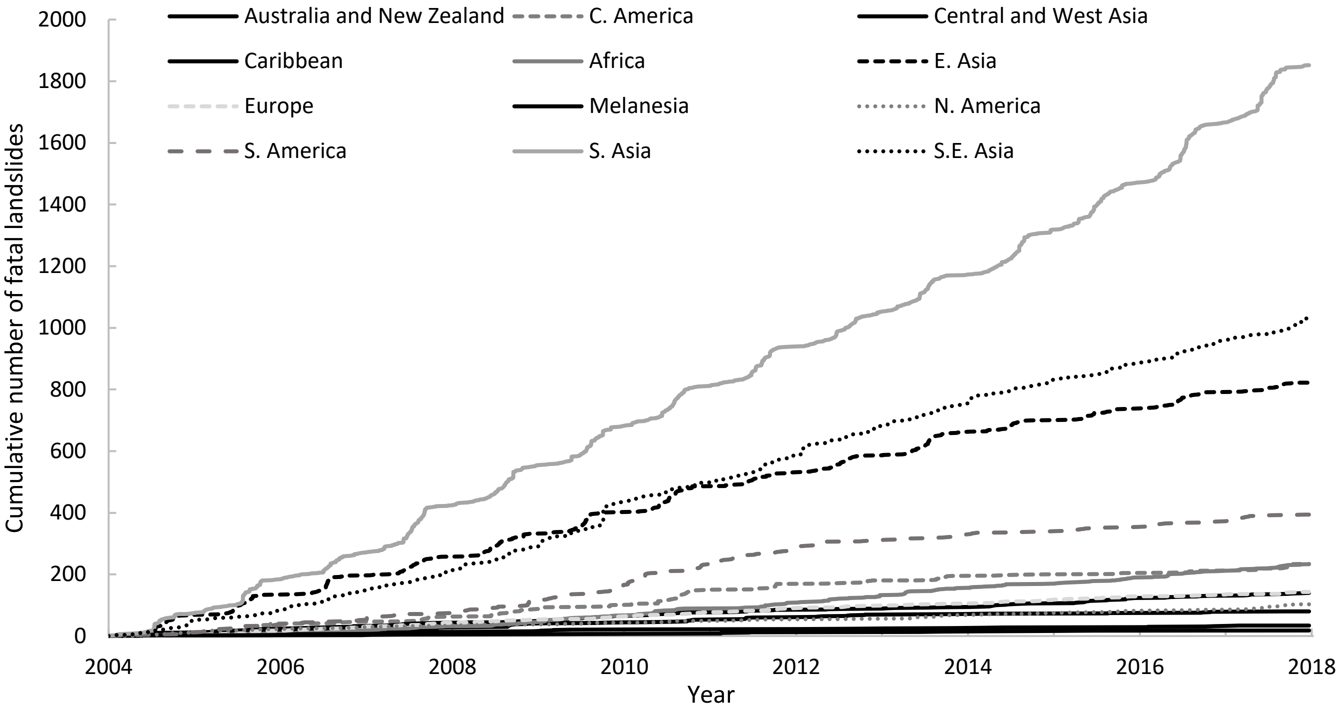

Figure 1: The number of recorded fatal landslides by geographical area between 2004 and 2018 inclusive. Note that the vast majority of losses are focused in Asia and Latin America.

to landslides when they occur, low capacity to rescue survivors and poor medical facilities that result in reduced survival rates for injured victims.

This point is illustrated in Figure 2, drawing upon experience from Nepal, which indicates the ways in which rural road development can lead to increased rates of landslide losses in mountain areas. The flowchart illustrates the ways in which inadequate control of the development of the road, and the management of it once constructed, can lead to higher rates of landslide loss than is necessary. The flow chart signposts the ways in which effective intervention could reduce the likelihood of economic and social loss from the landslides, benefitting the communities for whom the road had been constructed.

Similar configurations of vulnerability to loss occurs in many other settings in less developed countries, including for example the development of communities on marginal lands on the margins of cities (favelas), the development of hydroelectric schemes, the development of mines, etc. In each case there are similar factors (e.g. poor site selection, suboptimal emergency response, inadequate medical care) and unique ones (e.g. in the case of the development of settlements a key factor may be poor management of waste water).

Table 1: The total number of fatal landslides, and the associated loss of life, by major geographical region from 2004 to 2017 inclusive.

Region	Number of fatal landslides	Number of fatalities
S. Asia	1852	18266
SE. Asia	1033	12559
E. Asia	822	12594
S. America	394	5044
C. America	234	3520
Africa	233	3476
Europe	143	358
C. and W. Asia	140	729
N. America	103	194
Caribbean	80	4637
Melanesia	34	135
Australia & New Zealand	18	29

The remainder of this paper will focus on two key elements of landslide loss, and its management, in less developed countries. The first part examines in detail landslides losses associated with above-ground mining and quarrying activities, whilst the second part uses a detailed national case study, in this case Nepal, to try to understand better the patterns in time and space of landslide fatalities.

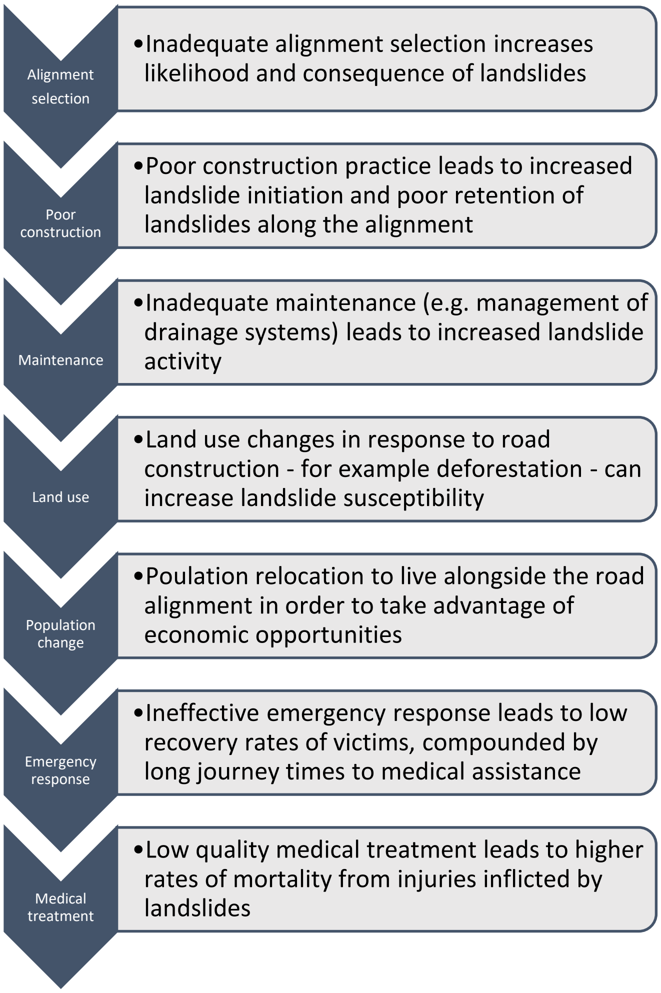

Figure 2. An illustration of the ways in which poor practice in the design, construction and management of a rural road in Nepal can lead to increased loss of life from landslides. Inadequate emergency response is also a significant factor, as are poor medical facilities, often with long journey times.

3 LANDSLIDES ASSOCIATED WITH ABOVE-GROUND MINING

It has long been established that landslides are a substantial hazard in above-ground mining and quarrying operations (hereafter termed simply as mining). Of course they can also be a consequence of subsurface extraction (for example Fathi Salmi *et al.* 2016 describe a landslide at Nattai North, the largest active landslide in Australia, induced by coal mining beneath the Sydney Basin escarpments). Slope instability can occur in the walls of the mining excavation, in mine waste piles (spoil or slag heaps), in tailings facilities and in associated infrastructure, such as the route ways for haul roads, pipelines, conveyors and railways. Landslides can also be induced in the landscape around the mining facility. On occasions, the establishment of a mine has destabilised existing dormant landslides, either within the curtilage of the mine or in the surrounding terrain. For example, Griffiths *et al.* (2004) describe the reactivation of a 35 million m^3 landslide during construction of the Ok Tedi gold and copper opencast mine in the Star Mountains of Papua New Guinea. This landslide had huge economic, social and environmental costs, polluting over 1,000 km of the downstream watercourses and disrupting the lives of over 50,000 people. It is likely that the costs of this landslide, and the resultant release of tailings, exceed the benefit of the mine over its entire lifespan.

In above-ground mining, instability can occur across a wide range of scales, from small individual blocks falling from rock slopes to very large-scale instability across the entirety of a high wall. In the case of the 2013 Bingham Canyon landslide in Utah, the volume of the two closely-spaced failures was about 70 million m^3 (Pankow et al. 2014), which makes it one of the largest landslides of any type recorded in North America. This landslide disrupted mining operations for a prolonged period, damaged mining equipment and led to extensive reprofiling of the mine slopes to improve stability.

In terms of the management of mining operations in more developed countries, the 1966 Aberfan landslide in South Wales, which involved a rotational landslide and subsequent flowslide in a coal waste spoil tip, marked a turning point in the understanding of landslides associated with mining activity. The failure, which led to the deaths of 144 people (of whom 116 were children in a school buried in the waste), and its subsequent public inquiry, led to a very significant improvement in the management of landslides in well-regulated mines and quarries, and of the waste that they generate. There has been extensive research to understand the behaviour of both rock slopes and mine waste, the development of best practice for mining operations and the development of new approaches for monitoring slope behaviour. However, as this paper will show, landslides associated with mining remain frequent in many part of the world, and their incidence is increasing with time, leading to rising losses. This is an unsustainable and unacceptable position, and urgent attention is required. In some cases, most notably the management of tailings, responsibility for the facilities usually lies with companies domiciled in developed countries, so this is not simply a less developed country problem.

As such, this part of this paper presents a call to arms with regard to the management of slopes in and around mines. There should be no acceptance that the current level of human, economic, social and environmental loss from mining landslides is acceptable. In particular, the levels of loss of life are deeply problematic.

4 THE GLOBAL BURDEN OF MINING RELATED LANDSLIDES

The rising cost of landslides associated with mining was initially highlighted by Froude and Petley (2018); the analysis presented here builds upon that work, providing a longer dataset and more intensive analysis.

In total, between 1 January 2004 and 31 December 2018, 410 mining landslides that caused a fatality (referred hereafter as fatal mining landslides) were recorded, causing the loss of 2,794 lives in total. The cumulative total number of fatal mining landslides over the 15 year period show a clear increasing trend with time (Fig. 3). The most expensive landslide in terms of loss of life was the Myitkynia landslide in Myanmar on 21 November 2015, which caused 214 fatalities, although it is worth noting that the Córrego do Feijão tailings dam flowslide at Brumadinho in Brazil on 25 January 2019 (which is outside the period of this study) killed 308 people. In terms of loss of life, the ten most costly fatal mining landslides over the study period are listed in Table 2. All occurred in less developed countries in S.E. Asia, Africa and E. Asia. It is particularly notable that Myanmar (Burma) has a high incidence of mass fatality mining landslides. This is associated with the very poorly regulated jade mining activity in Kachin State. This is covered in more detail below.

The cumulative total number of fatalities shows the same trend (Fig. 4), although this is a considerably noisier pattern due to the effect of occasional mass fatality events that cause a stepped increase in the cumulative total. The median number of fatalities in each event is three lives lost, showing that the majority of the landslides involve a comparatively small number of victims, often the result of small-scale rock slope collapses during mining operations.

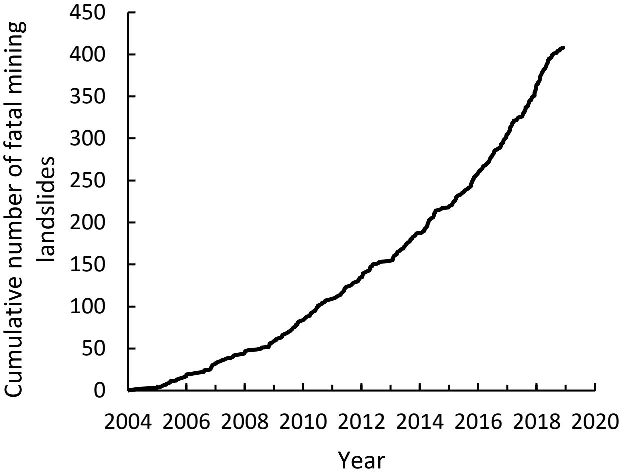

Figure 3. The cumulative total number of fatal mining landslides since 1 January 2004.

Table 2: The largest, in terms of loss of life, fatal mining landslides recorded in the study period.

Date	Location	No. fatalities
21/11/2015	Myitkyina, Myanmar	214
28/03/2013	Maizhokunggar, China	83
04/06/2009	Chongqing, China	72
09/04/2015	Myitkyina, Myanmar	70
23/06/2013	Ouaka, C. African Rep	62
13/08/2012	Orientale, DRC	60
10/07/2014	Unknown location, DRC	60
16/08/2006	Poura, Burkina Faso	55
25/12/2015	Myitkyina, Myanmar	55
12/01/2016	Myitkyina, Myanmar	40

Analysis of the impact of these events in terms of the number of lives lost suggests a pattern that is consistent with landslides caused by other processes (Petley 2012), in which the largest number of events cause just a single fatality (Fig. 5). Events causing two fatalities are almost equally as common, perhaps reflecting working practice in mines and quarries (where people rarely work alone). Perhaps surprisingly there are comparatively large numbers of events causing 3-4 fatalities and 5-8 fatalities. Events with higher numbers of deaths than this are substantially more unusual.

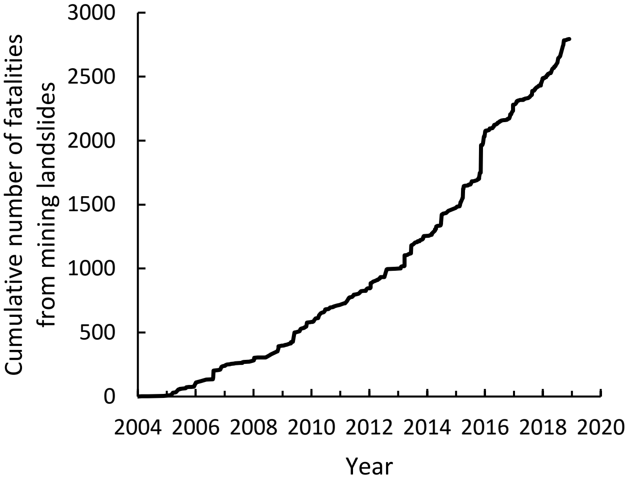

Figure 4. The cumulative total number of fatalities from mining landslides since 1 January 2004.

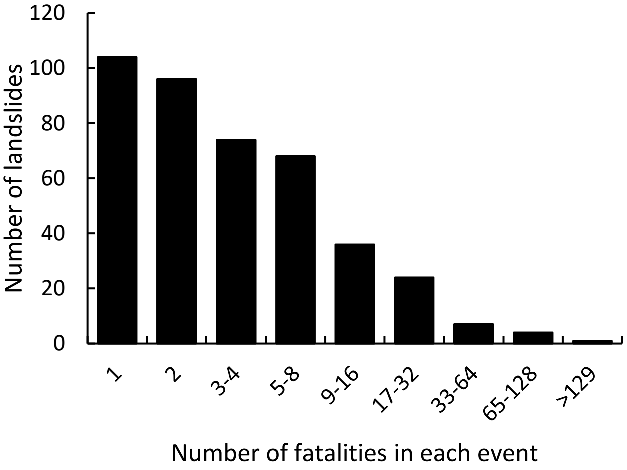

Figure 5. The size distribution of the number of fatalities in mining landslides from 2004 to 2018 inclusive.

Larger fatal mining landslides have beena recorded, in addition to the 2019 Brumadinho tailings dam failure noted previously. The largest mining-induced landslide that I have identified to date was the 1899 Sumitomo Besshi bronze mine landslide with debris flow disaster in Niihama, Shikoku, Japan in which it is reported that 512 people died. The 19 July 1985 Stava tailings dam failure in Italy took the lives of 268 people (Chander and Tosatti 1995; Luino and De Graff, 2012), whilst the 9 May 1993 landslide at the Nambija mining settlement in Zamora-Chinchipe Province in SE Ecuador is believed to have killed about 300 people.

In all datasets of this type, there is an issue as to whether a rising trend with time reflects genuinely increased landslide impacts or is a result of improving data capture with time. Figure 6 shows the annual total number of fatal mining landslides per annum, whilst Figure 7 shows median number of fatalities in each year. The number of recorded fatal landslides has increased dramatically over this period, most notably from 2012 onwards. If improved data capture lies is the cause then it is likely that there will be a proportional increase in the number of low fatality events being captured (events with mass fatalities are likely to be widely reported, whereas those with small numbers of fatalities are less likely to be reported – see Petley 2012). The median value varies considerably, and was notably higher in the early years of the dataset than in the second half. It is likely therefore that some of the initial increase in the number of recorded fatalities is the result of better data capture, but this is unlikely to account for all of the significant increase since 2012. It is likely that this results in part from an increase in fatal mining landslide occurrence.

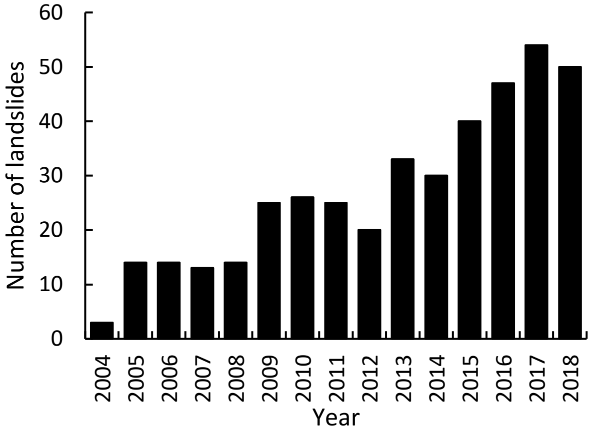

Figure 6. The annual number of fatal mining landslides from 2004 to 2018 inclusive.

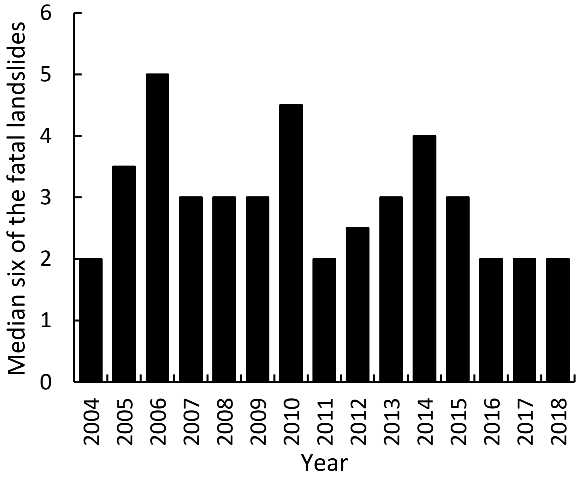

Figure 7. The median number of fatalities in fatal mining landslides from 2004 to 2018 inclusive.

The reasons for this increase in fatal mining landslides may be complex. A possible explanation is a significant increase in mining activity in less developed countries over the same period. One potential driver is global mining production, reflecting that an increase in mining activity might be associated with an increase in related landslides. Figure 8 shows the volume of global mine production since 2004, extracted from Reichl *et al.* (2018).

Over the study period there has been a notable increase in the volume of mineral extraction, representing an increase in extraction of about 50%, although the rise in landslide events is not perfectly synchronous. Interestingly, there appears to be a strong relationship with total mining production from less developed countries (Fig, 7), which is where lower standards of mine management and operations may apply, and is where most of the fatal mining landslides occur.

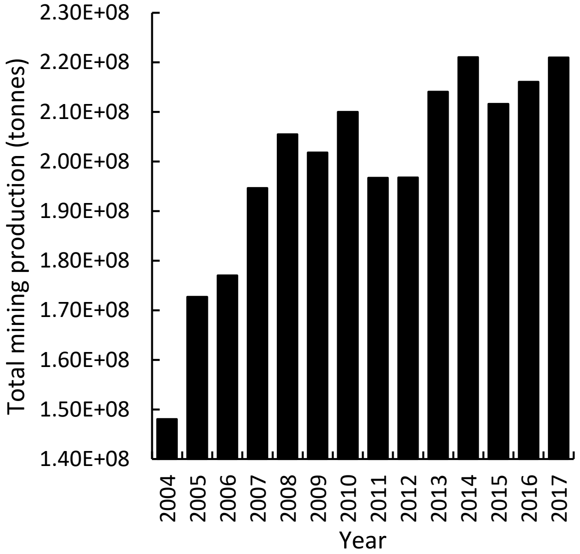

Figure 8. The increase in mine production from least developed countries from 2004 to 2017 inclusive. Data from Reichl *et al.* (2018).

As noted above, it is likely that one of the reasons for the dramatic increase in mining-related fatalities is the growth in unregulated, or poorly regulated, mining. In the fatal landslide dataset, or an attempt is made for each event to determine whether it has occurred in a mine that is legal (i.e. operating within, and complying with, a legally enforceable regulatory framework) or illegal (i.e. operating outside, or failing to comply with, a legally enforceable regulatory framework). The latter includes landslides that affect artisanal mining and that of people scavenging for ore on mine waste piles. Fatal mining landslides are classified into a tripartite scheme – legal, illegal and unknown, with the latter covering events in which it has proven impossible to determine their legal status. It is likely that the majority of landslides in the unknown category were actually illegal.

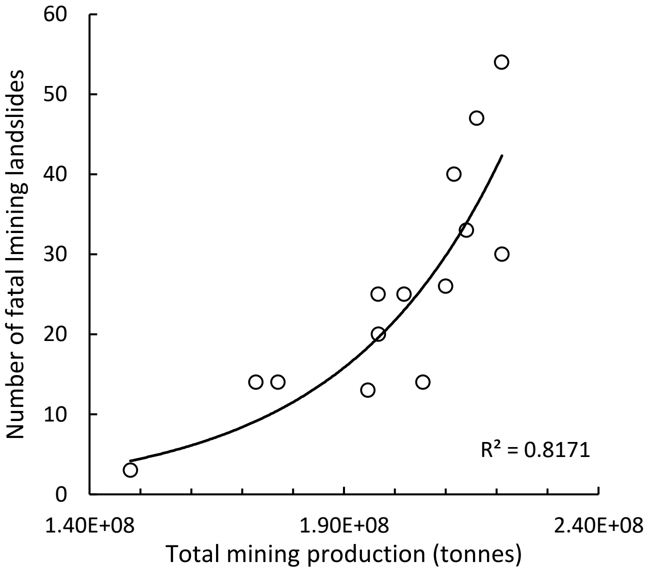

Figure 9. The relationship between mine production from least developed countries and the number of fatal mining landslides from 2004 to 2017. Data on total mine production from Reichl *et al.* (2018).

Figure 10 shows the cumulative occurrence of mining landslides according to the legal status over the study period. Until about 2009 landslides were roughly evenly distributed between the three classes. Since then there has been a marked acceleration in rate of occurrence of both legal and unknown mining landslides, but with a lower acceleration in the legal group. Since 2017, when mining landslides became a greater focus of this research, increased effort has been placed into determining the legal status of fatal mining landslides. As a result the number of events in the unknown category is lower since this point. There is a corresponding increase in the number of mining landslides in the illegal category, supporting the extrapolation that most of the fatal mining landslides in the unknown category are likely to have occurred in illegal mines.

Thus, most of the increase in the occurrence of mining landslides appears to be associated with illegal or unregulated activity in less developed countries. This comes in two key forms. In some cases, there is simply no attempt to regulate mining in a meaningful manner. Large-scale operators act

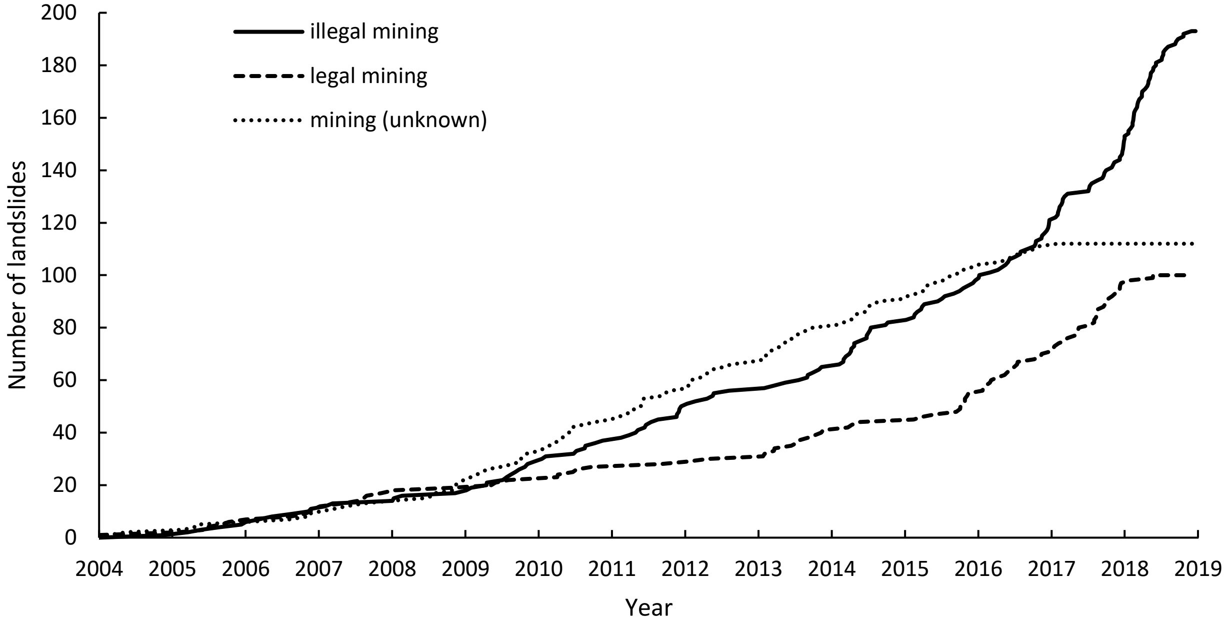

Figure 10: The cumulative number of legal, illegal and unknown mining landslides recorded over the study period.

with impunity, accepting high levels of loss amongst the work force in order to maximize yield and profit. In other cases, small scale (artisanal) mining of ore and/or scavenging in waste deposits occurs, also with no formal management of risk. In other areas, illegal mining activities occur even though regulations are in place.

The pattern is clearer when loss of life in mining landslides is considered. Figure 11 shows the occurrence of fatalities in mining landslides, classified in the same tripartite scheme as for Figure 10. In this case it can be seen that the proportion of fatalities associated with illegal and unknown mining landslides has increased substantially in recent years.

Thus, it appears that poor regulation of mining activities might explain much of the increase in mining landslides, and the resultant loss of life. As such, these are preventable fatalities.

There is a considerable literature on the role of artisanal mining and scavenging in the economic development of less developed countries. This type of mining can play a key role in lifting individual out of poverty – for example, Hilson (2002, p. 3) notes that:

"It is important to clarify that, in spite of experiencing its share of environmental- and health-related problems that adversely impact human quality-of-life, small-scale mining plays a pivotal role in alleviating poverty in the developing world, and contributes significantly to national revenues and foreign exchange earnings. Though these important socio-economic contributions make small-scale mining an indispensable economic activity".

The solution is not to ban this type of mining – indeed the solution may be the diametric opposite, i.e. to legalise (and thus legitimise) it, to support it (for example in the management of risk) and to provide education and training in order to make operations safer and more sustainable.

In Figure 11, an analysis is undertaken of the geographical location of the fatal mining landslides. Included in the graph are the four regions that contribute the vast majority of the deaths – Africa, SE. Asia, S. Asia and E. Asia. The trends with time are notably different. The rate of landslide events for East Asia is approximately constant with time. A similar trend is also shown by SE. Asia, although in this case the annual rate is higher. However, SE. Asia also shows a notable increase in rate in the last two years of the study for reasons that are not clear. This may simply be noise in the data. For Africa and S. Asia, a notable increase in the rate of fatal mining landslides occurred from about 2010 onwards. The rate of acceleration occurred in about 2016, when the rate of recorded mining landslides approximately doubled. The reasons for this increase in mining related activity in South Asia in particular is not clear, and is worthy of more detailed investigation. There is very little literature on patterns of mining landslides in time and space in less developed countries.

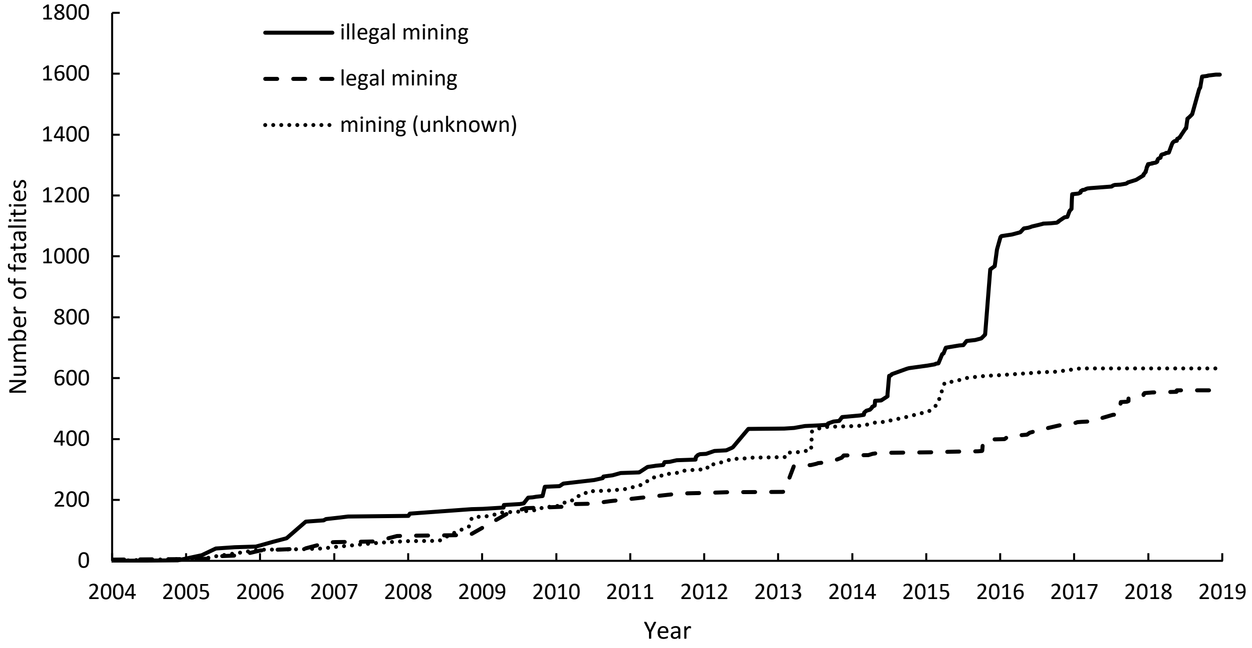

Figure 11: The cumulative number of fatalities from legal, illegal and unknown mining landslides recorded over the study period.

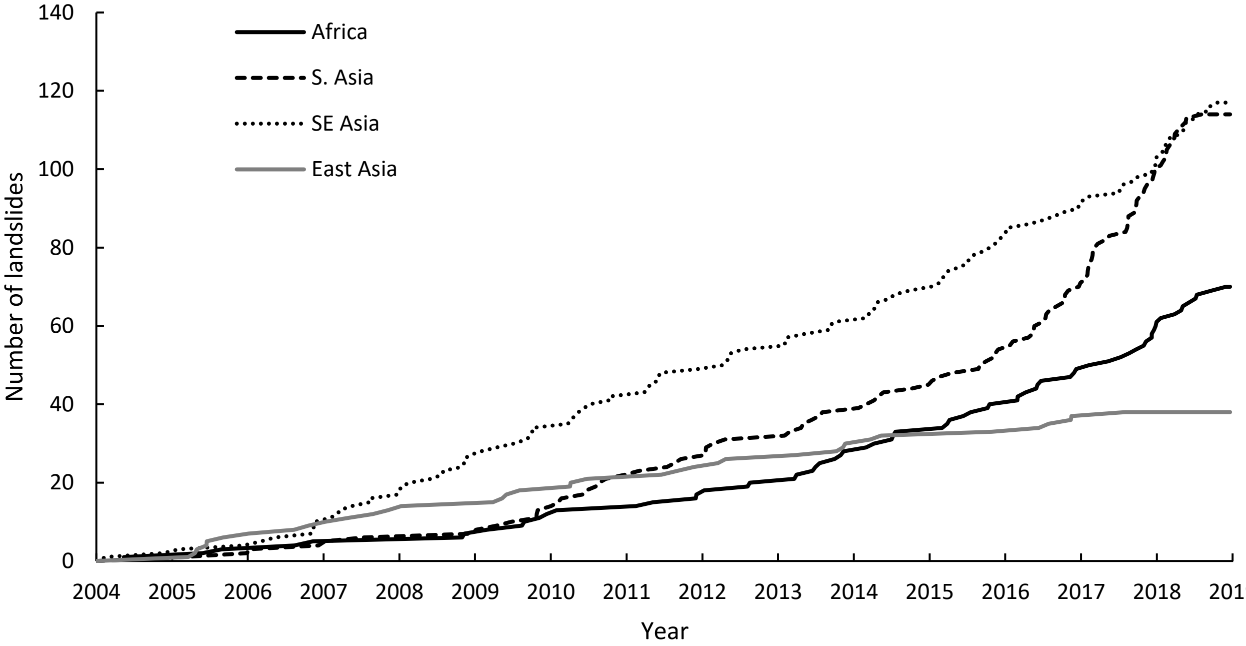

Figure 12: The cumulative number of fatal mining landslides recorded over the study period for the four main geographical regions.

In terms of loss of life, a slightly different pattern emerges (Fig. 13). For three of the areas there has been only a small change in the rate at which lives are lost in mining landslides. This reflects the fact that the majority of the landslides recorded kill only a small number of people (typically one or two individuals), whilst the total fatality data is dominated by a smaller number of events that kill larger numbers of people, in common with observations for landslides more generally (Petley 2012).

A part of the explanation for the dramatic increase in fatalities in SE. Asia is the rise in landslide events in Myanmar (Burma) noted previously. Since 2014 there has been a dramatic increase in the number of recorded mining landslides in Myanmar – these 30 events to the end of December 2018 killed at least 660 people, of

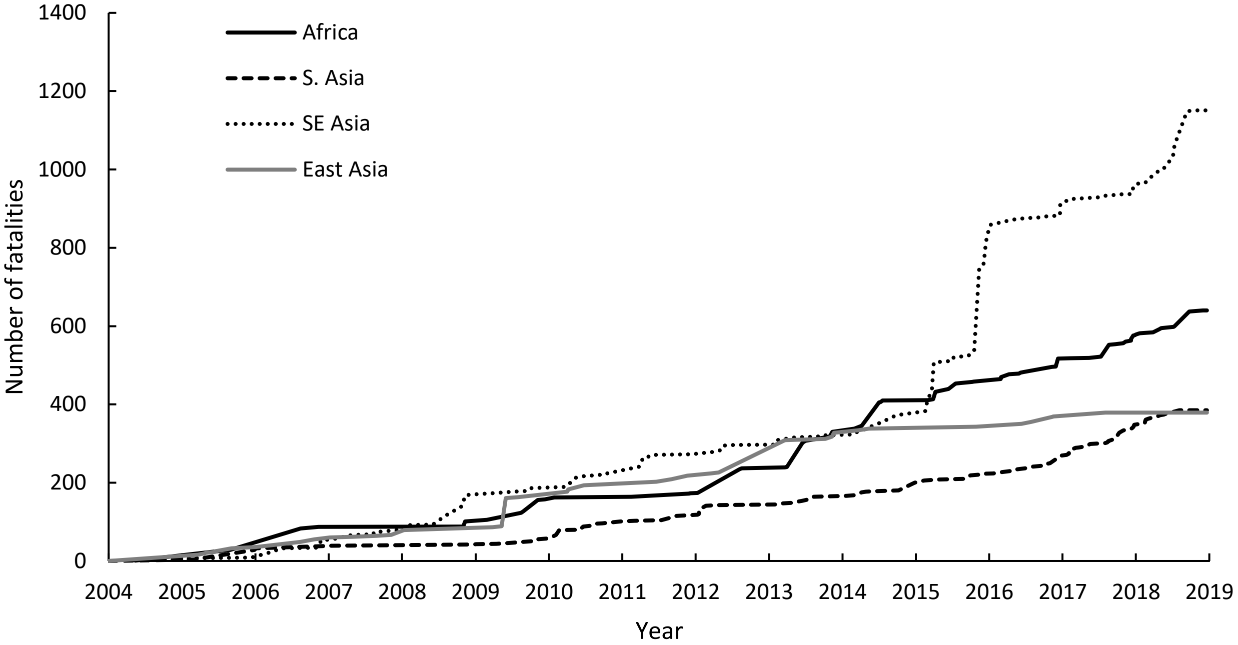

Figure 13: The cumulative number of fatalities from mining landslides recorded over the study period for the four main geographical regions.

which 214 fatalities occurred in the in a major landslide on 21 November 2015. These landslides primarily involve two key scenarios. Many of the deaths are associated with the loss of people scavenging for minerals in the waste piles left by the larger mining operations. In many cases tipping appears to be undertaken without proper management practices. In a monsoonal climate, with periods of exceptional rainfall, unmanaged spoil tips have high potential for instability.

On the other hand, there is also significant loss of life from the failure of rock slopes during mining operations, often at the larger mine sites, but sometimes associated with artisanal mining. Both of these types of landslides are the result of inadequate regulation and poor mining practices.

The high rate of failure of slopes associated with mining in Myanmar is the consequence of a particular set of circumstances. Most of the landslides occur in the vicinity of Hpakant (sometimes called Phakant) in Kachin State, a major centre of jade mining. This area produces the world's best quality jadeite, which is in high demand, especially in China. Revenues are in excess of US$30 billion per annum. Over 100 mines are operated in this area, but it has frequently been described as the "wild, wild east" due to its poor regulation and management.

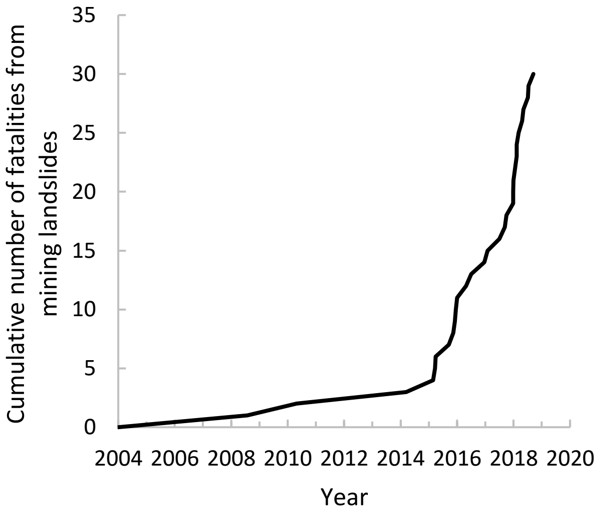

Figure 14. The cumulative number of mining landslides recorded in Myanmar over the study period.

Figure 14 demonstrates a distinct change in the rate of mining landslides from about 2014, and by 2015 a steep trajectory had been established that has been maintained subsequently. On 8 November 2015, Myanmar held a general election, aimed at establishing a democratic government. One expectation was that the new government would establish a much higher level of regulation around the awarding of mining permits and oversight of mining operations. Those managing the jade mining activities reportedly dramatically increased the scale of mining in 2014 to maximise profits, which appears to have resulted in greater levels of fatal mining landslides. The government suspended the provision of new permits for jade mining in 2016 and a new legal framework for gemstone mining was enacted in 2019. However, enforcement of regulations has proven impossible. Images from Hpakant show mine workings that are excessively tall and steep; unmanaged spoil tips and villages located extremely close to slopes being cut. Additional problems are clear – an Environmental Management Plan (Coffey Myanmar and Valentis Services 2016) noted that the mining companies typically used abandoned workings as spoil sites, rather than transporting the waste to regulated dumping sites, and that the short duration of permits (five years) disincentivises good practice. The abandonment of mines after five years typically leaves them in a poor state, increasing the risk of slope instability. Unsurprisingly, these mine sites are often reoccupied by artisanal mining, increasing the risk.

Myanmar represents probably the most profound exemplar of the ways in which social conditions, allied with poor regulation, drives up the occurrence and impact of fatal mining landslides. Good mine planning and practice, guaranteed through appropriate regulatory frameworks that are properly enforced, could reduce the human, social and environmental costs to a fraction of the current level. It is unclear as to whether the 2019 Gemstone regulations will reduce the toll. However, on 24 January 2020 at least one scavenger was killed in a landslide on a jade mine spoil tip.

5 THE MOBILITY OF MINING LANDSLIDES

A key factor in determining loss of life in mining landslides is their mobility, which determines both the distance over which they will travel and the forces that they can impose on structures and objects along their path. There are some studies on this topic; most notably, the mobility of large failures ($\geq 40{,}000$ m^3) on high wall slopes was examined by Whittall *et al.* (2016) using a dataset of 105 events. In general, these failures were found to behave in a manner similar to large failures in other settings, with a strong control exerted by slope angle, fall height and, to a lesser degree, volume. However, a subset of the records were found to have exceptional mobility. These occurred where the failure involved weathered, saturated, collapsible rock mass materials. In these materials, high pore pressures can develop after failure that can reduce basal friction, permitting long runout distances to develop. This behaviour is in keeping with that seen in other large slope failures.

Other studies have examined the mobility of individual mining landslides (e.g. Blight and Fourie 2005 examined specific examples, including Aberfan) or of certain types of mining landslides (e.g. Siddle *et al.* 1996 examined the mobility of rapid coal waste landslides in the South Wales coalfield), but there are few analyses that synthesise the data. To examine this issue I have compiled a dataset on mining related landslides from a variety of sources, including individual landslide case studies and datasets that collate series of examples. These are benchmarked against the mobility dataset for large landslides provided in Legros (2002). Included in the dataset are tailings failures, compiled by Bowker and Chambers (2015, 2017, 2017), and kept up to date by the same team. For the major events in which sufficient data was available, I have calculated the vertical extent of the landslide, adding 27 records to the dataset, allowing the mobility of tailings failures to be compared with other landslides.

One way to assess the mobility of landslides is to examine the relationship between the vertical extent of the landslide (the vertical difference between the landslide crown and the toe of the landslide deposit) with the landslide length. Fig. 15 displays the data for mining landslides, excluding tailings failures, which will be considered below. Approximately 65% of mining landslides display mobility that is consistent with more conventional failures, but a significant proportion display considerably greater mobility.

However, a different picture emerges when mobility is considered in terms of the relationship between runout length and landslide volume (Fig. 16). In this case the runout length is in general consistent with that of other large landslides, such as rock avalanches. This was also noted by Whittall *et al.* (2017) for mining rock slope failures, and may be a consequence of lower fall heights and, in some cases, in constraints on runout distance imposed by the mine site.

However, the best test of landslide mobility is the so-called Fahrböschung angle, which is the ratio of the landslide height to its length. This ratio is usually compared with the landslide volume (Corominas 1996). Using this measure, pit wall

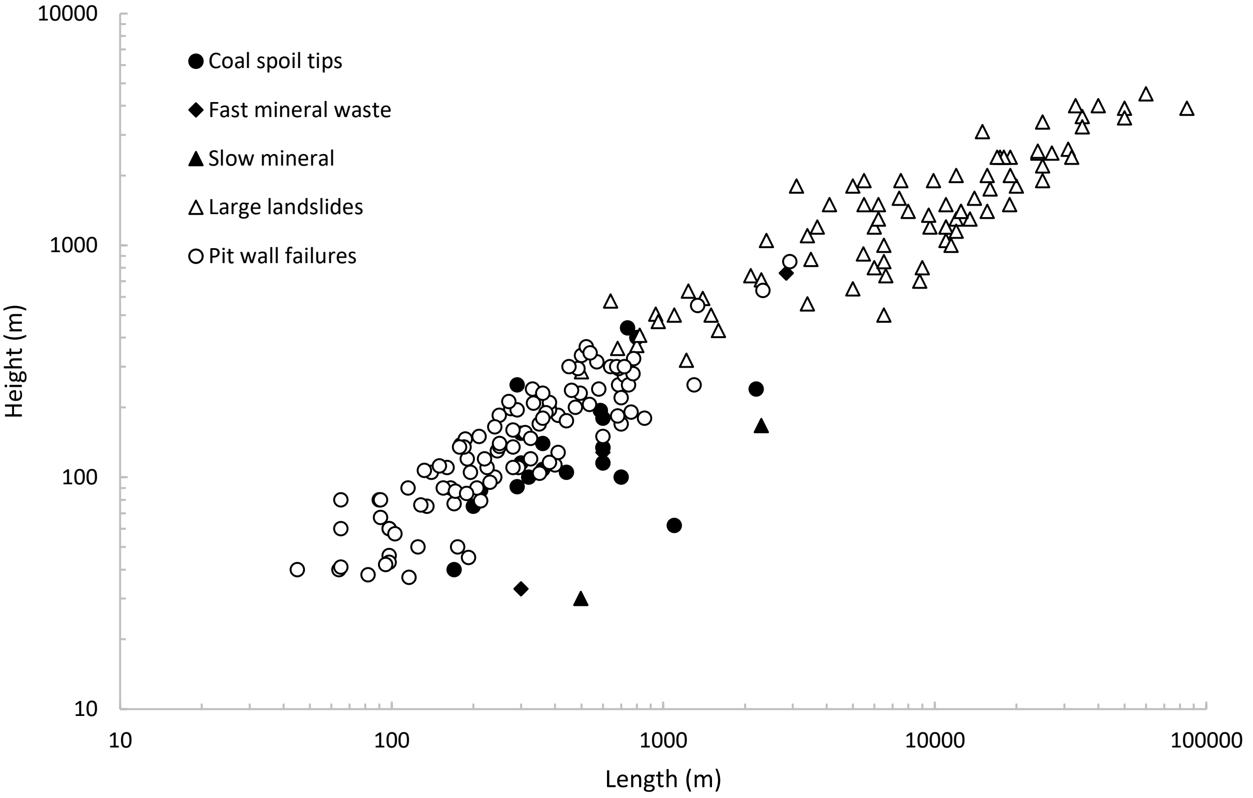

Figure 15: The relationship between height and landslide runout distance for the mining landslides. Large landslide and pit wall data included for comparison, from Legros (2002) and Whittall *et al.* (2016).

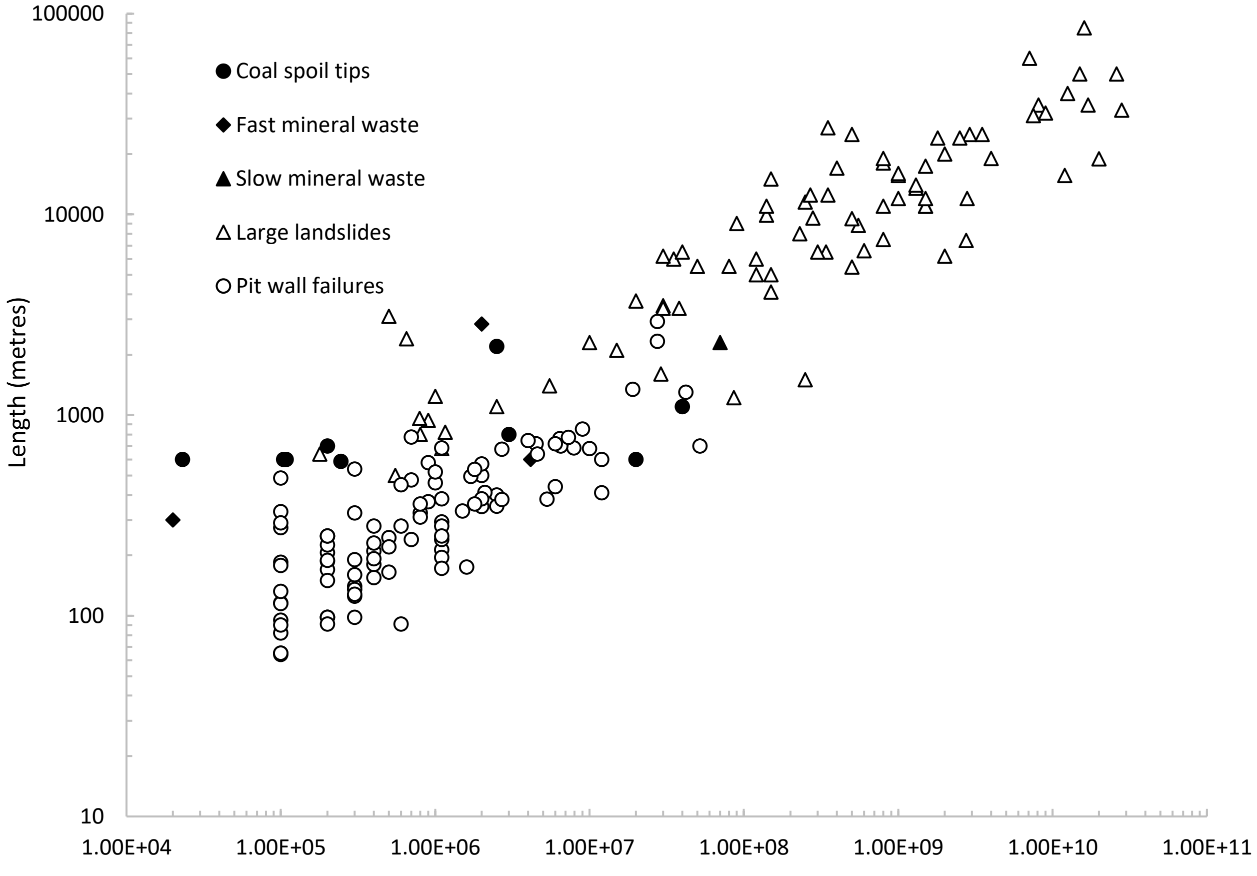

Figure 16: The relationship between landslide runout distance and volume for the mining landslides. Large landslide and pit wall data included for comparison, from Legros (2002) and Whittall *et al.* (2016).

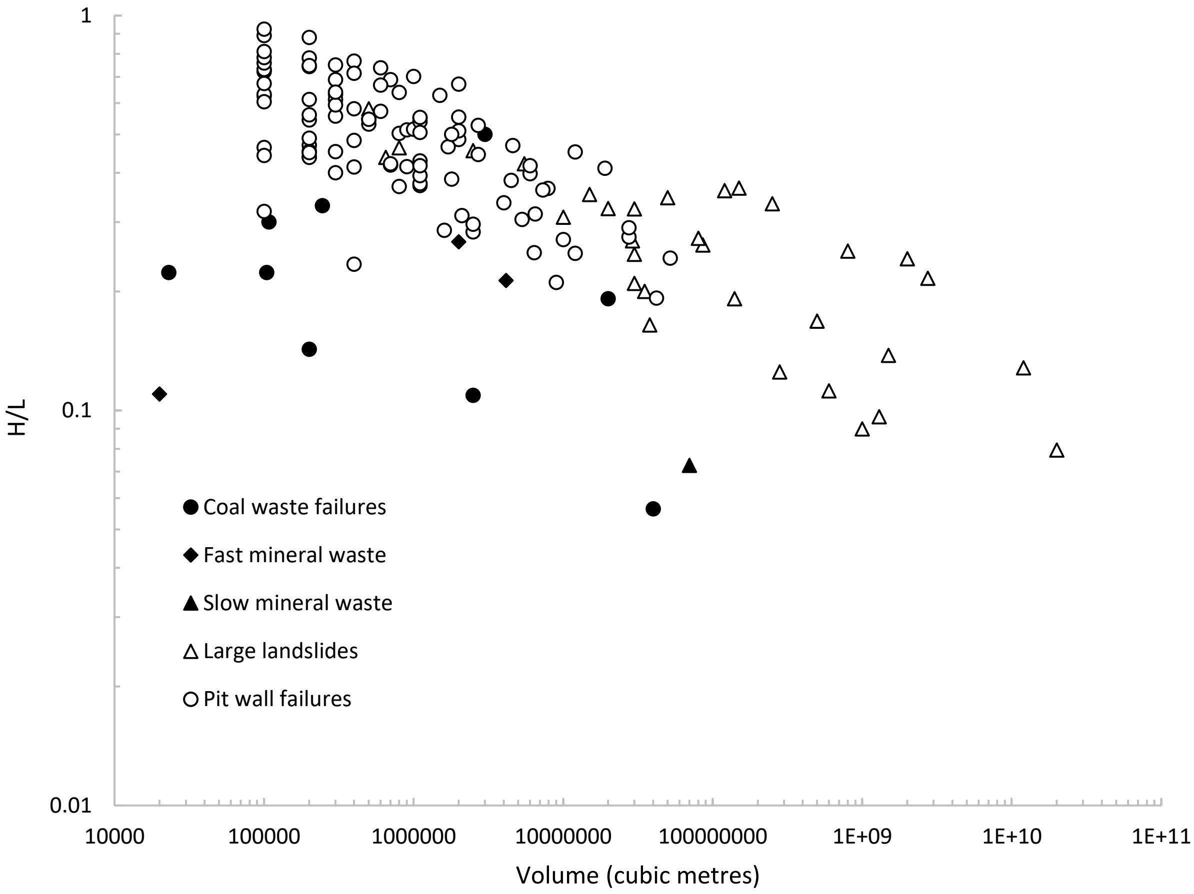

Figure 17: The relationship between the Fahrböschung angle (H/L) and volume for the mining landslides. Large landslide and pit wall data included for comparison, from Legros (2002) and Whittall *et al.* (2016).

failures show lower mobility than large landslides, but with the same overall trend in which mobility increases (i.e. H/L reduces) with increasing volume (Fig. 17). In general the mining landslides show greater mobility (lower values of H/L), although with a somewhat variable pattern. In one case, the Arcturus landslide in Zimbabwe in 1978, mineral waste showed exceptional mobility, with a Fahrböschung angle of just 6°.

Thus, the Fahrböschung angle of mine waste landslide is in general lower than that of large landslides, which themselves are generally considered to have high mobility. The most likely explanation is the presence in mine waste of crushed materials as well as large clasts, and in many cases high pore water pressures. This probably accounts for the comparatively high levels of loss of these failures; once movement has started there is high damage potential. Clearly, the best mitigation is good waste management to avoid the initiation of failure. Pit wall failures show lower mobility, but have high potential to affect workers with the site. Thus, their fatality rate is also high.

6 THE PROBLEM OF LANDSLIDES IN TAILINGS

Morgenstern (2018) noted that *“there is a crisis associated with concern over the safety of tailings dams and lack of trust in their design and performance. This crisis has resulted from recent high-profile failures of dams at locations with strong technical experience, conscientious operators, and established regulatory procedures”*. This was penned even before the disastrous Feijão tailings dam at Brumadinho in Brazil In January 2019, which killed 308 people. Such failures occur frequently, with devastating impacts in terms of loss of life, environmental degradation, economic cost and social cohesion. Interestingly, Independent Expert Panel (2015) for the Mount Polley tailings dam failure asserted that *“The Panel does not accept the concept of a tolerable failure rate for tailings dams. To do so, no matter how small, would institutionalize failure.*

First Nations will not accept this, the public will not permit it, government will not allow it, and the mining industry will not survive it." Despite this, failures of tailings dams continue to occur. Morgernstern (2018) assessed 15 major tailings dam failures between 1980 and 2015, determining that all but two involved failures of engineering and two involved failures of regulation.

A key factor in the damage caused by tailings failures is the mobility of the resultant landslide. The Fahrböschung angle has been calculated for 27 tailings dam failures. The events themselves, and their associated volumes and landslide lengths, were accessed from the World Mine Tailings Failures catalogue, described in Bowker and Chambers (2015) and Bowker and Chambers (2016). The height difference has been assessed from cartographic and digital data. This has not proven to be possible for all landslides in the World catalogue, but reliable information has been obtained for the 27 examples examined here.

Fig. 18 examines the Fahrböschung angle – volume relationship for the tailings landslides relative to the other types of landslides described above. Note the change in the H/L scale compared to Fig. 17. The results are highly revealing in terms of the risk posed by tailings landslides. The mean H/L ratio of these 27 landslides is 0.120, corresponding to a Fahrböschung angle of 6.81°. By comparison, the mean Fahrböschung angle for the large landslide dataset is 20.1° and for the mine waste landslides 32.2°. Thus, the tailings dam landslides display exceptional mobility, in most cases far in excess of that displayed by other mining landslides. The explanation for this set of exceptional values is that the vertical difference in most tailings dam landslides is comparatively low – the tallest tailings dam, in terms of dam foot to crest, in the failure dataset analysed here was 110 m, and they typically discharge into river channels that have moderate to low gradients. Nonetheless their runout distances tend to be very large.

To understand this extreme mobility, the official report of the Fundão Tailings Dam Review Panel, which reported on the major failure in Brazil in 2015, provides insight. In this case, failure occurred as a result of liquefaction in loose, saturated sand in the left abutment of the dam. At the point of failure, the volume of now liquefied material was large. As such the behaviour is more akin to that of sensitive clays, which also undergo large-scale liquefaction at the point of failure.

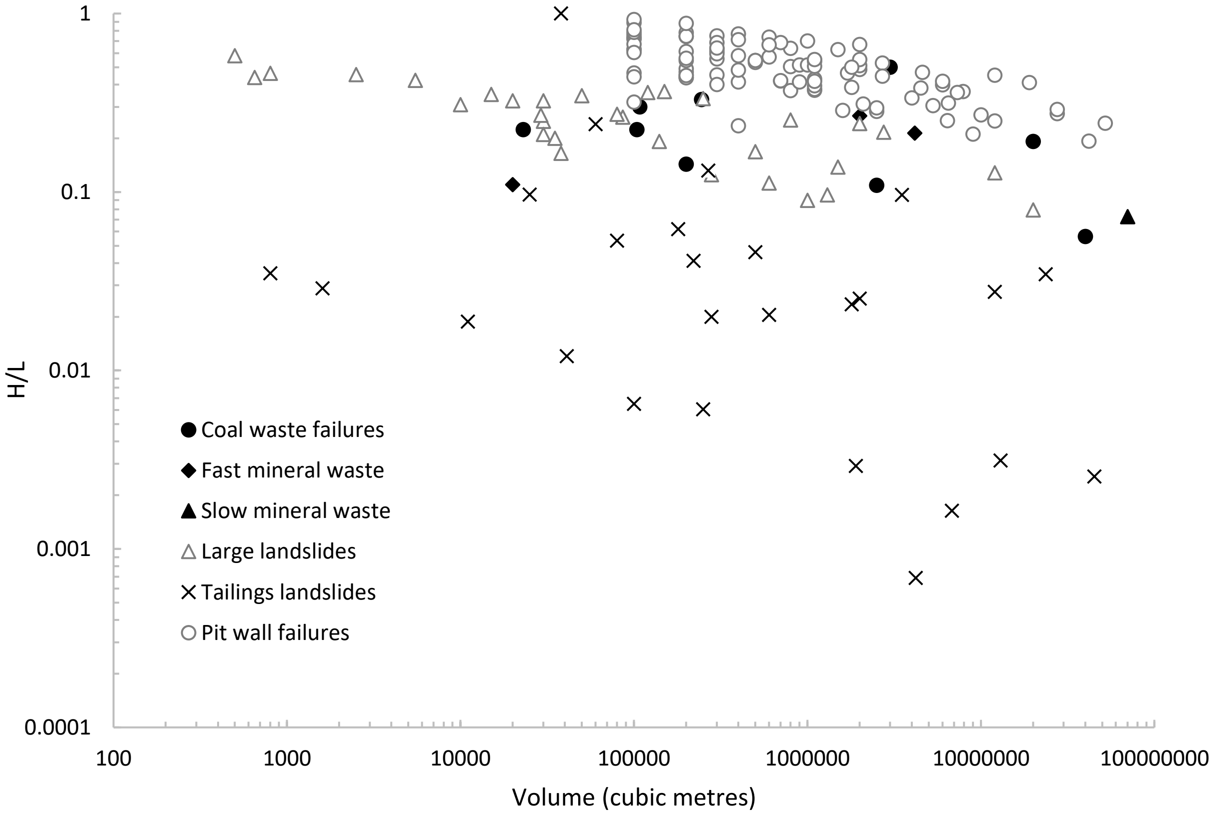

Figure 18: The Fahrböschung angle – volume relationship for mining landslides, with the tailings data added.

In addition, tailings dam failures frequently involve large volumes of water within the facility – in some cases there is standing water on the surface of the tailings at the time of failure. The tailings themselves are often compacted to a comparatively low degree – sometimes less than in the design. And finally, in the case of the Marinara (Brumadinho) tailings dam failure, the tailings may have developed a cemented structure that generated a very brittle, and thus very rapid, failure.

This exceptional mobility post-failure serves to underscore the conclusion of the Independent Expert Panel (2015) for the Mount Polley tailings dam failure that tailings dam failures have no level of tolerable risk. Given that many tailings facilities are located in areas that are seismically active, this presents severe challenges to the management of these facilities in the long term.

7 AN EXAMPLE OF LANDSLIDE LOSSES IN A DEVELOPING COUNTRY

As noted in Section 2, South Asia is the global hotspot for human losses from landslides. The major contributors to this toll are India, Pakistan, Nepal, Bangladesh, Sri Lanka and Bhutan. Many, but by no means all, of the recorded landslides occur in the Himalayan Mountains during the summer (SW) Monsoon. The 2005 Kashmir Earthquake in Pakistan and India and the 2015 Gorkha Earthquake in Nepal were both a major cause of landslides and associated fatalities; such events are comparatively rare but trigger many failures. An inventory of the Gorkha earthquake landslides for example includes 47,200 records (Xu 2018).

In previous work, I have examined the impact of landslides in Nepal, in particular highlighting the impact of road construction (Petley *et al.* 2007) and the monsoon (and thus climate change) in landslide initiation. Here I provide an update to this work.

In the study period for this paper (2004-2018 inclusive), and excluding landslides associated with the 2015 Gorkha Earthquake, I have recorded 501 fatal landslides in Nepal, costing 2339 lives. This total would be much higher if the impacts of the Gorkha Earthquake were to be included, but these are poorly recorded in most cases. The landslide at Langtang is thought to have killed approximately 350 people, and there were many reports of landslide-induced fatalities in rural areas. Experience from elsewhere suggests that in such an earthquake landslides are likely to be the cause of 25-33% of the total number of fatalities Petley *et al.* 2006). If so, based on a total of 9,168 people reported killed or missing this would put the number of landslide-related deaths in the Gorkha earthquake in the range of 2,300 to 3,000, albeit with a high level of uncertainty.

Fig. 19 displays the number of non-seismic fatal landslides, and the associated human losses in Nepal over the study period. The number of fatal landslides recorded shows an upward trend over

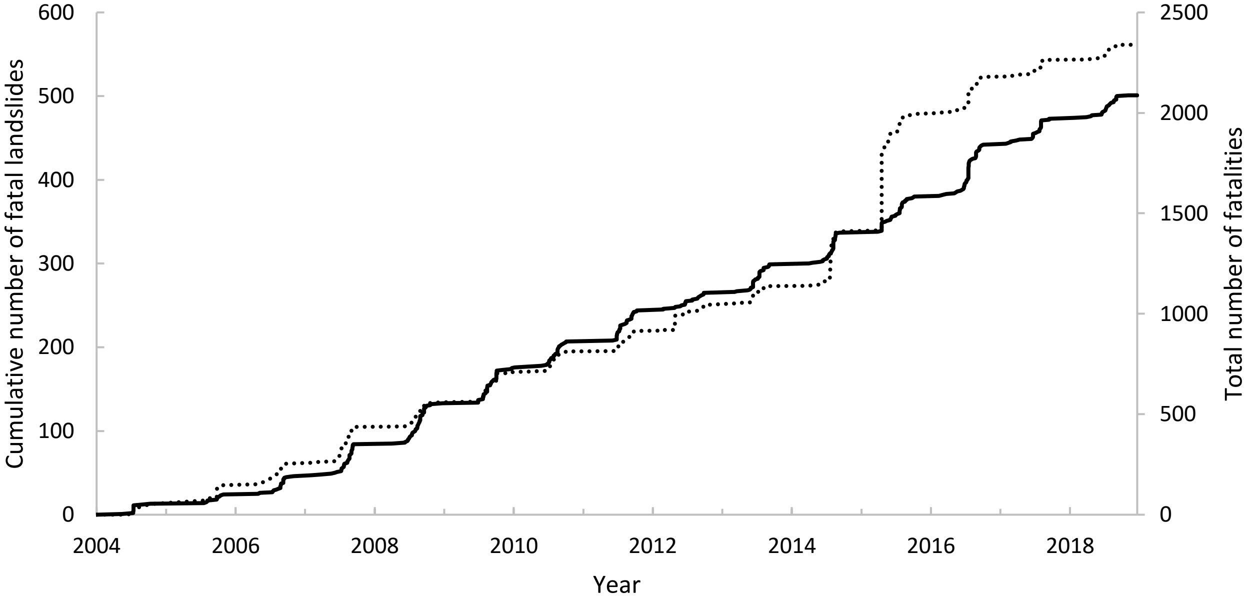

Figure 19: The cumulative total number of fatal landslides, and resultant fatalities, in Nepal over the study period.

this 15 year period (46 in 2006-2008; 121 in 2016-2018 for example, although this might be associated primarily with a lower than expected number in the early years of the study. As noted in previous studies (Petley *et al.* 2007), the occurrence of landslides in Nepal is strongly seasonal, reflecting the intensity of the summer SW monsoon (Fig 20). Landslides peak in in July and August, with a slow decline through September and October. There are almost no landslides in the period between November and April, reflecting the dry months in Nepal.

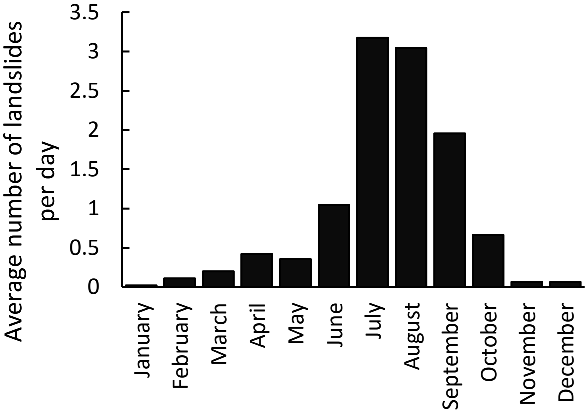

Figure 20: The monthly occurrence of non-seismic fatal landslides in Nepal between 2004 and 2018 inclusive.

Figure 21 shows the distribution of fatal landslides across Nepal in the study period on a base map of the topography using a digital elevation model. The fatal landslides are clustered in the middle hills, across the whole of Nepal, with comparatively few events recorded in the high mountain areas to the north and in the Terai Plain to the south, illustrating the control of topography on the occurrence of landslides. Fig. 22 shows the same data mapped with annual precipitation – note the clusters of landslides in areas with high precipitation totals, especially in central Nepal. Fig. 23 shows the same data with population density; notably, in areas with low population few landslides are recorded.

Fatal landslides require a combination of topography, precipitation and people to occur; thus the distribution is a combination of the three maps shown in Figs 21 to 23.

In the last two decades there have been substantial improvements in our understanding of landslides, including for example:

1. Better understanding of landslide mechanisms and processes;
2. Improved capability in short term (using local instrumentation) and medium term

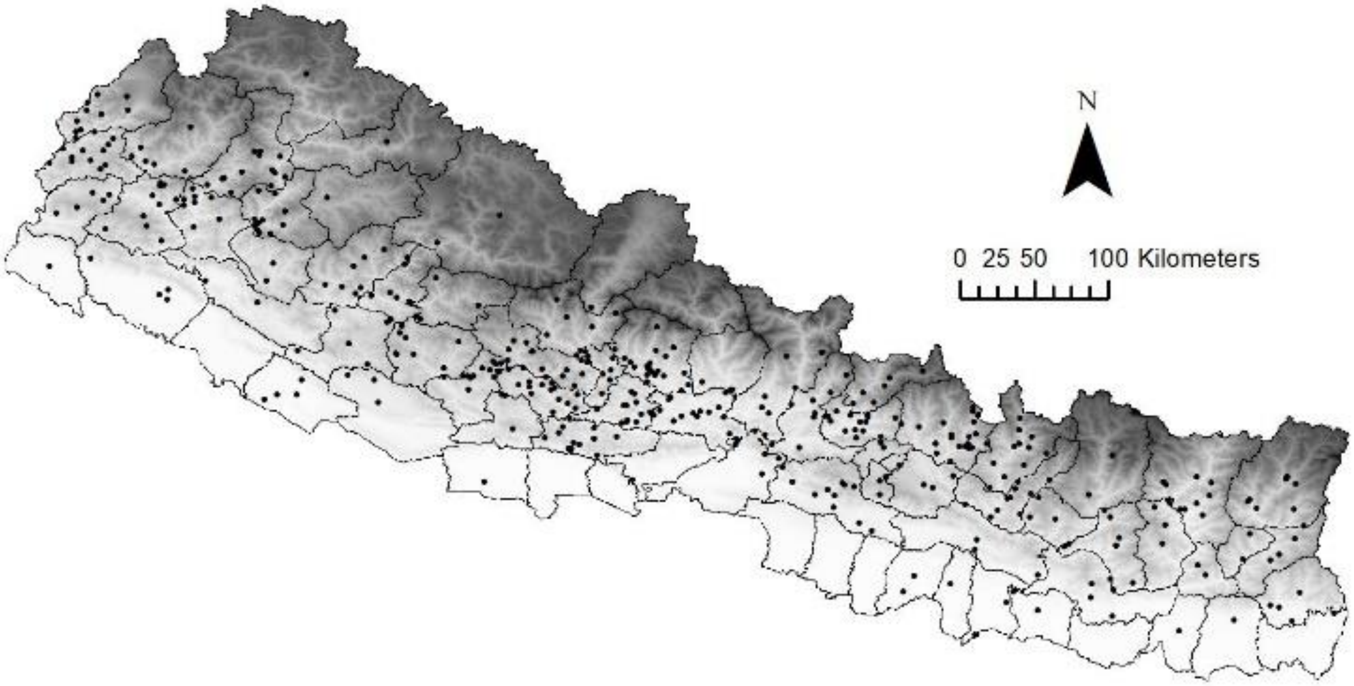

Figure 21: The distribution of fatal landslides across Nepal, over the study period, overlaid onto a digital elevation model.

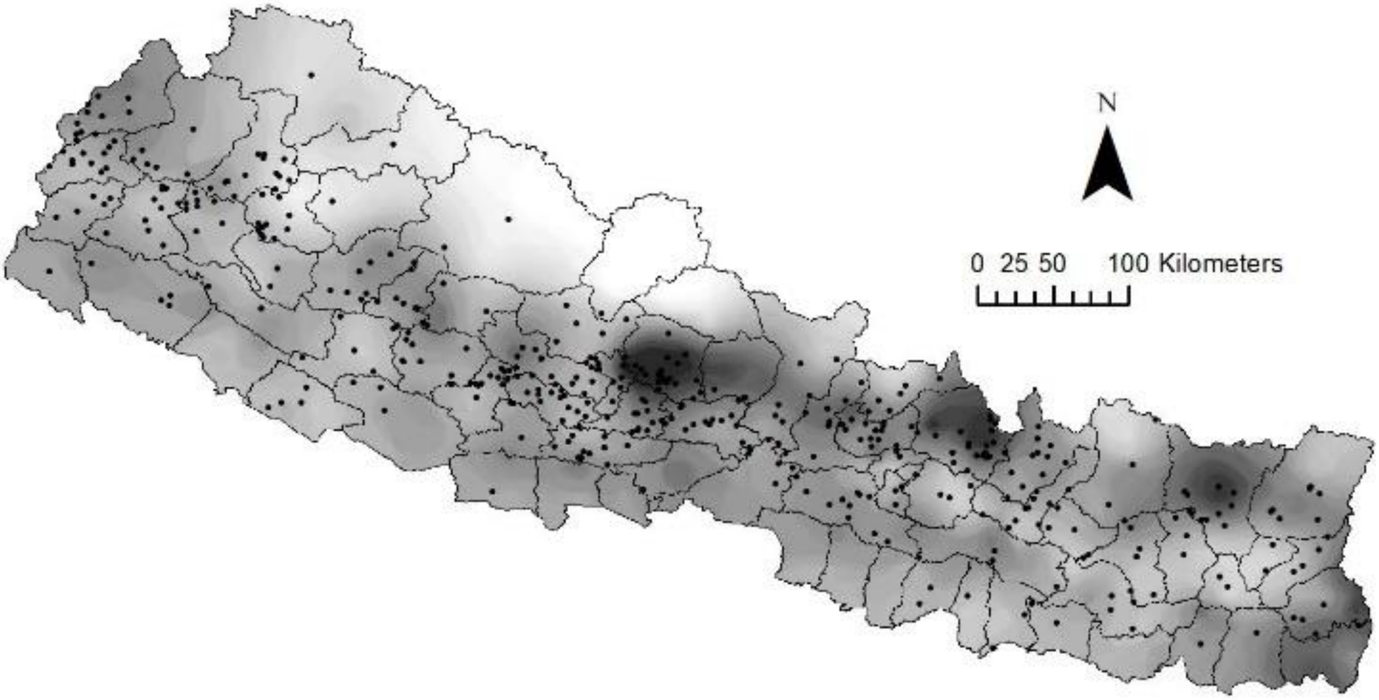

Figure 22: The distribution of fatal landslides across Nepal, over the study period, overlaid onto a map of total annual precipitation.

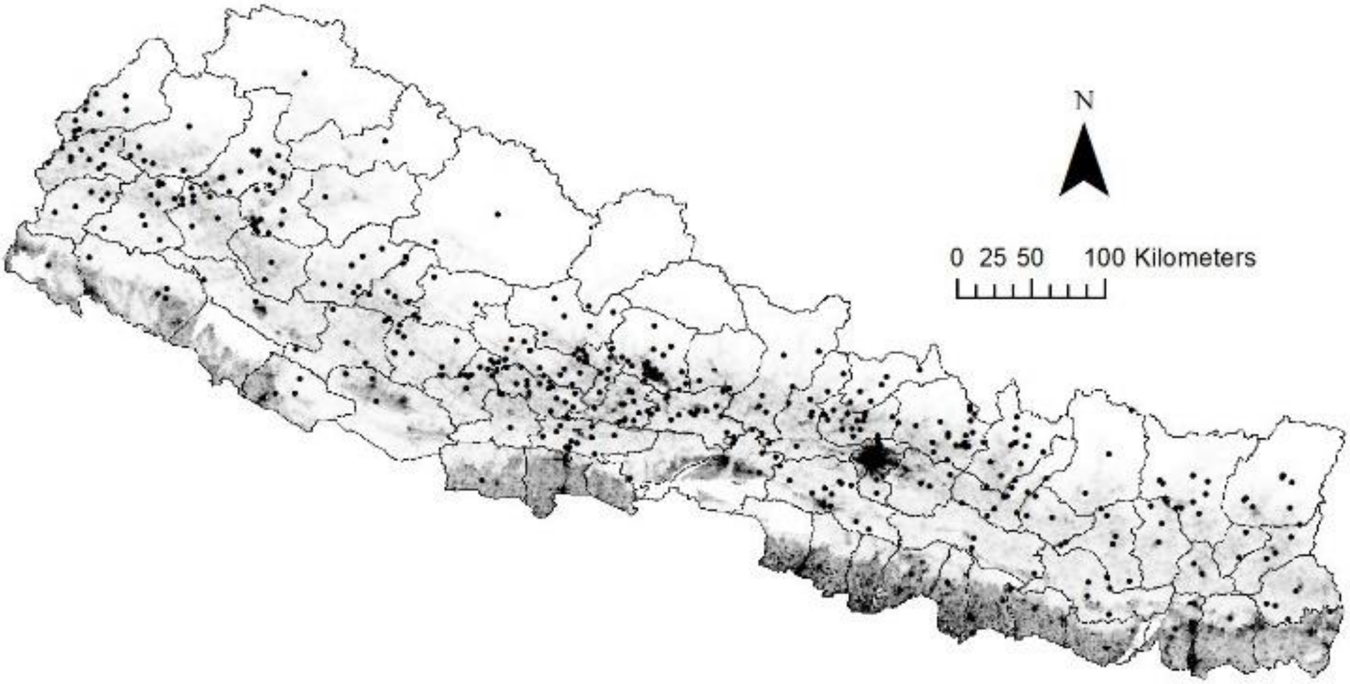

Figure 23: The distribution of fatal landslides across Nepal, over the study period, overlaid onto a map of population density.

(using rainfall forecasting) anticipation of landslide events;

3. New analytical tools for slope behaviour, including three dimensional slope stability analysis and coupled analyses of slope performance;
4. New spatial tools for the detection of landslides, including daily satellite imagery, UAVs, enhanced LIDAR and new generations of InSAR data;
5. Enhanced techniques for slope stabilisation, including the widespread deployment of soil nails and new bioengineering approaches.

It is therefore disappointing that these improvements are not being translated into a reduction in landslide losses in Nepal. This is not a Nepal-specific problem; similar trends are seen in many other less developed countries, whilst losses remain low on a per capita basis in most developed countries.

That targeted programmes can reduce landslide losses is not in dispute. The best example remains the systematic programme of slope safety management in Hong Kong, implemented in 1977 and maintained to this day, via the Geotechnical Engineering Office (GEO, formerly called the Geotechnical Control Office). This programme has reduced the risk associated with manmade slopes across Hong Kong by about 75%, and as a consequence the region has not suffered a landslide fatality in over a decade. Elements of the Hong Kong approach have been incorporated elsewhere, such as by the Slope Engineering branch of the Public Works Department in Malaysia, with some success. But these examples are rare.

Effective landslide management programmes require a host of elements to be in place, as evidenced by Hong Kong. These include:

a. ***Long term, high level political commitment to address slope safety***. Managing dangerous slopes requires advanced engineering and technical skills. In many cases in which slope safety is implemented late in the national development process, considerable retrofitting and re-engineering of slopes is required, necessitating the presence of a dedicated agency or body to prioritise, coordinate and audit the work. This can only be achieved with long term political commitment.
b. ***Availability of resource***. Slope management is undoubtedly expensive. Effective slope management requires that the nation or region both has resource that it can commit to slope safety (which is not the case in many countries) and that it is willing to prioritise the funds in this way.
c. ***An understanding of the causes of the problem***. As this paper has shown, the causes of losses in different areas vary substantially. In Hong Kong, poorly engineered slopes were a substantial cause of losses; in Nepal, inadequate road engineering is a major problem. Effective landslide risk management requires that these issues are understood, allowing resource to be targeted. An effective approach is to progressively make safe the most dangerous slopes, requiring that knowledge is sufficiently advanced that a raking exercise can be accomplished.
d. ***Availability of appropriately qualified professionals.*** Effective management of slopes requires a cadre of highly qualified professionals, primarily in geotechnical engineering but also in geology, hydrology, bioengineering etc., with appropriate professional support. In many developing countries training, supporting and retaining such a cohort is extremely challenging, especially when there is a shortage of appropriately skilled people in developed countries, which draws away professionals needed for this work.
e. ***A culture of safety.*** Effective slope management requires that organisations, such as those managing highways, railways and pipelines, and those involved in construction, recognise the importance of safety, and are willing to encourage their staff to take action to eliminate dangerous practices. In many cases this is not the case, as evidenced by the mining failures described above. Building and maintaining a safety culture is crucial, but requires strong and effective leadership.
f. ***The capacity to enforce regulation***. The challenge associated with mining landslides, articulated in the early part of this paper, emphasises the role of effective regulatory structures, and effective regulations to implement, in maintaining slope safety. There needs to be an appropriate mechanism to ensure that regulations are formulated and

that they are then enforced. In many less developed countries regulations are in place, but their implementation is severely lacking. Corruption often plays a major role especially in sectors with large capital investment.

g. ***Effective planning processes***. In many more developed countries, effective planning is a key mechanism to ensure that buildings and infrastructure is not located in areas of high residual slope hazard. Thus, in New Zealand there is an effective mechanism of resource consents designed to ensure that development is appropriate. Resource consents are strongly enforced by regional authorities. In many less developed countries, development is undertaken without any process of planning permission, allowing structures to be constructed in inappropriate locations, inadequate draining to be installed, and slopes to be cut or filled without appropriate designs being in place.

Hong Kong had a particular advantage in that its geographical area was comparatively small. In countries spread over a larger geographical area, the problems are much more acute. In such cases, the impetus for better slope management will usually come from central or state-level government. Sadly, this remains rare in most less developed countries.

8 CONCLUSIONS

The risks associated with fatal landslides is predominantly located in less developed countries that have high population density, steep slopes and seasonal rainfall and/or high seismic hazard. Parts of Asia bear the highest costs, although other parts of the world are substantively impacted too. There is little evidence that losses are being reduced, despite substantial improvements in our understanding of landslides and in their management.

Unfortunately, without effective action losses are likely to remain high, or even to increases, as population densities rise, rainfall intensities increase as a consequence of global heating, and uncontrolled infrastructure development continues in upland areas.

This paper has sought to highlight some of the reasons why landslides cause such problems in poor countries. Human activities, such as unregulated mining, impose a risk burden on the population that is unacceptable. In addition, companies domiciled in developed countries often fail to apply appropriate mining and engineering practice in less developed countries, allowing tailings facilities (for example) to collapse, with catastrophic consequences. For these facilities, a new approach is required that assumes an intolerance to risk, and in effect over-engineers structures to ensure safety. Such an approach is being discussed widely.

In other locations, such as Nepal, poor road construction in upland areas may play a significant role. Poorly located and engineered roads increase the likelihood of failure, and sere to locate people (road users) in places that are vulnerable. These problems are exacerbated if the population relocates to live beside the road; in these cases the individual risk can increase many times over.

But the failure to lower losses can be attributed in part to the challenges in effectively managing slope risk. That this is possible has been demonstrated in Hong Kong, but it is expensive and it is challenging to implement across a large geographical area. In such places, effective slope management requires concerted action at government level that includes regulation, capacity building and resourcing. This remains a major challenge in many parts of the world.

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