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Trends in landslide occurrence in Nepal

**David N. Petley · Gareth J. Hearn · Andrew Hart ·
Nicholas J. Rosser · Stuart A. Dunning · Katie Oven ·
Wishart A. Mitchell**

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Abstract Nepal is a mountainous, less developed kingdom that straddles the boundary between the Indian and Himalayan tectonic plates. In Nepal, landslides represent a major constraint on development, causing high levels of economic loss and substantial numbers of fatalities each year. There is a general consensus that the impacts of landslides in countries such as Nepal are increasing with time, but until now there has been little or no quantitative data to support this view, or to explain the causes of the increases. In this paper, a database of landslide fatalities in Nepal has been compiled and analysed for the period 1978–2005. The database suggests that there is a high level of variability in the occurrence of landslides from year to year, but that the overall trend is upward. Analyses of the trends in the data suggest that there is a cyclicity in the occurrence of landslide fatalities that strongly mirrors the cyclicity observed in the SW (summer) monsoon in South Asia. Perhaps surprisingly the relationship is inverse, but this is explained through an inverse relationship between monsoon strength and the amount of precipitation in the Hill District areas of Nepal. It is also clear that in recent years the number of fatalities has increased dramatically over and above the effects of the monsoon cycle. Three explanations are explored for this: land-use change, the effects of the ongoing civil war in Nepal, and road building. It is concluded that a major component of the generally upward trend in landslide impact probably results from the rural road-building programme, and its attendant changes to physical and natural systems.

Keywords Landslide · Vulnerability · Monsoon · Precipitation · Roads

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D. N. Petley (✉) · N. J. Rosser · S. A. Dunning · K. Oven · W. A. Mitchell
International Landslide Centre, Department of Geography,
Durham University, Durham DH1 3LE, UK
e-mail: d.n.petley@durham.ac.uk

G. J. Hearn · A. Hart
Scott Wilson Kirkpatrick Ltd, Scott House, Basing View,
Basingstoke, Hampshire RG21 4JG, UK

1 Introduction

In recent years it has become apparent that landslides represent a far greater hazard globally than had been previously assumed, both in terms of economic losses and fatalities (Petley et al. 2005a; Petley 2006). It is also now clear that the impact of landslides, certainly in terms of both economic losses and probably also with respect to deaths, is increasing with time (Brabb 1991; Alexander 1993; Guzzetti 2000; Schuster and Highland 2001; Petley et al. 2005a). The majority of fatalities and the highest costs from landslides in terms of proportion of GDP occur in less economically developed areas, particularly in the tectonically-active monsoonal and tropical cyclone affected areas of Asia and the Americas (Petley et al. 2005a). In terms of absolute economic losses the highest impacts are probably in mountainous, more developed countries with high levels of rainfall and/or seismicity, notably Canada, the United States, Japan and Italy (Brabb 1991). Indeed, in many mountain environments, landslides represent one of the most acute hazards, although in general their impact is seriously under-represented (Hewitt 1997).

Unfortunately, the causes of the increases in the occurrence and impacts of landslides are poorly quantified. A wide range of hypotheses have been proposed, many of which are generally accepted even though there is little empirical evidence to support them. These include:

1. Population growth (for example Alexander 1993; Alexander 2005). Population growth is considered to influence the impact of landslides first by ensuring that there are more individuals at risk and second by driving the development of increasingly marginal terrain, most notably landslide prone areas at the toe of slopes and on steep mountainsides;
2. Land-use change, most notably deforestation (see for example Schuster and Highland 2001; Alexander 2005). The loss of forests is thought to reduce the rate of evapotranspiration on slopes, leading to higher groundwater levels, to reduce cohesion through the loss of root strength and to increase overland flow, which enhances the rate of erosion (Crozier 2005). The effect of these changes is to render slopes increasingly sensitive to landslide triggers and to increase the mobility (i.e., the run-out velocity and hence distance) of slides once they have been initiated.
3. Urbanisation. The growth of cities, especially in less economically developed countries, leads to the growth of urban slums or shanty-towns on marginally stable slopes on the periphery of urban areas (Schuster and Highland 2001; Alexander 2005 for example).
4. Linear infrastructure development. The construction of transport infrastructure, especially roads, is considered to increase the probability of landslides as a result of undercutting and the application of surcharges as a result of the disposal of spoil and through the relocation of people who wish to take advantage of the economic opportunities associated with roadside sites (for example Sidle et al. 2006). Unfortunately, such sites are often more susceptible to landslides than are the locations of their original houses.
5. The effects of (anthropogenic) climate change, which might be changing rainfall distributions and intensities (Petley et al. 2005a).

Unfortunately, the actual impact of these changes in real terms is poorly quantified, such that in many cases these effects, although logical, are little more than anecdotal. Understanding these processes is undoubtedly important given the global cost of landslides. In addition, heavy investment is being made in mountainous areas of less economically-developed countries by a range of international organisations, including international development agencies such as the Inter-American Development Bank, the World Bank and the Asian Development Bank and national development agencies such as DFID (UK), JICA (Japan), Helvetas (Switzerland) and GTZ (Germany). In many cases this investment is focussed upon the development of rural access, for which the occurrence of landslides is a key issue. There is clearly an urgent need to try to quantify changes in the occurrence and impacts of landslides, and to develop an understanding of the causes of these changes through time. This understanding will help to target scarce resources in the most appropriate manner, and to improve the identification of areas and individuals at risk from the effects of landslides.

The aim of the study reported here is to compile and evaluate data regarding the temporal trends in landslide occurrence in Nepal in the period 1978–2005 and to use these data to attempt to understand the underlying causes of changes in landslide impacts through time. To do this, we have constructed a database of fatal landslides for the study period. This database has been analysed in terms of spatial and temporal distributions, with a particular emphasis upon the relationships with the distributions in time and space of potential triggering factors.

2 The study area

Nepal is a mountainous Himalayan kingdom with a surface area of 147,181 km^2 (Fig. 1). Globally, it is the country with the highest relative relief on earth, with

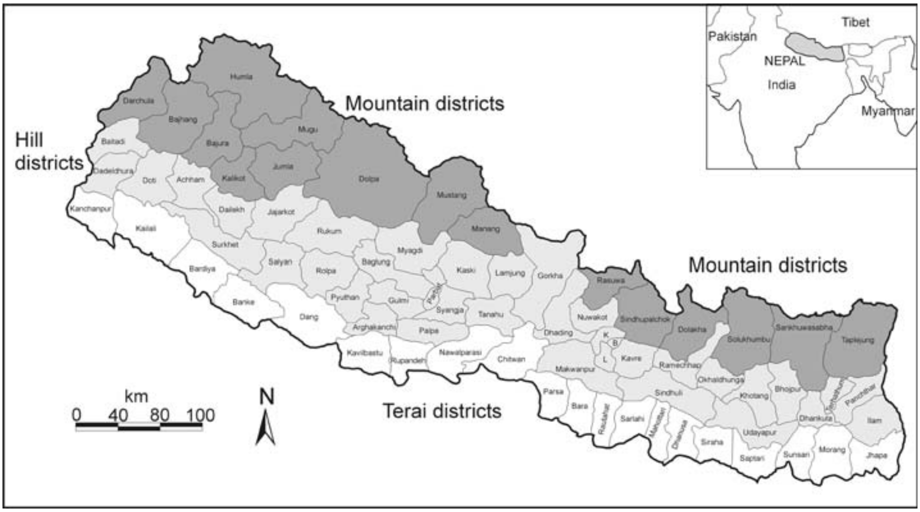

Fig. 1 A map of Nepal showing the subdivision of the country into Mountain, Hill and Terai districts. Inset is a thumbnail map showing the location of Nepal within South Asia

a lowest elevation of 70 m above sea level and a maximum elevation at the summit of Sagamartha (Mount Everest) of 8848 m. For management and development purposes the terrain of Nepal can be divided into three regions (Fig. 1). In the south of the country lie the Terai districts, representing 23.1% of the surface area of the country, whose topography mostly consists of flat alluvial plains. These districts have comparatively high population densities (48.5% of the total population of Nepal). In the far north lie the mountain districts, incorporating the remote mountain massifs of the High Himalaya, which comprise 35.2% of the land area of Nepal. These areas are however sparsely inhabited, supporting only 7.3% of the population. Between these two areas lie the Hill Districts of the Middle Himalaya, within which much of the terrain consists of alpine-height mountains and valleys (i.e., peaks reaching up to ca. 5000 m but valleys at less than 500 m asl). The population of this area, which includes the Kathmandu Valley, represents 44.2% of the national total.

As would be expected for a country with such an extreme range of elevations, the climate varies greatly, ranging from subtropical on the lowland plains to glacial in the high mountains. The climate throughout most of the country is strongly monsoonal. For the landslide-prone Middle Himalayan terrain the climate is cool and dry for much of the year, although the summer months (June-September) are warm and humid, with high levels of precipitation associated with the south-west Asian monsoon. The actual levels of rainfall during the monsoon period vary considerably from year to year, depending upon a range of climatic factors that are generally-considered to be associated with global and regional climatic systems (Shrestha et al. 2000).

It is well recognised that landslides occur extensively in the Himalayas (e.g., Owen et al. 1995; Sah and Mazari 1998; Barnard et al. 2001; Sarkar et al. 1995), and in particular within Nepal (e.g., Gardner and Gerrard 2000a; Petley et al. 2005b). An area such as the Himalayas should be expected to have a high level of natural landslide activity. In tectonically active mountain chains such as the Himalayas, natural landslides play a fundamental role in the evolution of the landscape, providing a mechanism through which a mass balance can be achieved between uplift and erosion. Landslides represent the most efficient process in non-glaciated (and possibly also in glaciated) environments through which material that has been advected into a mountain chain by tectonic processes can be released from the hillsides and removed. Thus, it is a mistake to consider that all landslides are the result of human activities, or that all landslide risk is socially "constructed". However, there is a clear anthropogenic influence in the occurrence of landslides in the mountainous areas of Nepal (see for example Gerrard and Gardner 2000a, b; 2002). Note though that except along road corridors most of the documented human-induced landslides are in reality comparatively small and shallow. Nonetheless human-induced landslides often have a substantial impact, especially in terms of loss of local agricultural productivity, which can have severe economic effects both locally and nationally. For example, the large failure at Krishnabhir in Dhading District, southwest of Kathmandu, led to the closure of the key arterial road linking Kathmandu with the Terai plains and thus with India for eleven days in August 2000, causing serious economic disruption to the capital city.

3 Methodology

For this study we have compiled a database of landslide fatalities for Nepal for the period 1978–2005 inclusive. This database was constructed using a variety of sources, including newspaper reports, government datasets, NGO documents, scientific papers and, where reliable, personal accounts. Sources of information were predominantly in the Nepali language, but English language information sources were also used when available. The most consistently available data for a landslide events provides the date of occurrence, location, trigger mechanism (i.e., heavy rain or construction for example), number of fatalities, number of injuries and the number of people missing. Less consistently reported, but recorded when available, were information on the type of landslide, size, rate of movement, damage to infrastructure and property, loss of farm animals and direct economic damage. In this analysis we have focussed upon temporal and spatial trends in the number of landslide fatalities each year, as these data are generally consistent throughout the dataset.

Considerable complexities and problems are associated with the construction of such databases. Critical amongst these are the following:

1. *Definitions of landslide*. There is a key need to think about how the term ‘‘landslide’’ is defined. There are two elements to this: first, technically there is a need to decide which events to include within the database. Thus, for example should a debris flow be included? If so, how can a differentiation be made between a debris flow and a hyper-concentrated flow? Second, how accurately do the reports used to compile the database achieve this differentiation? Hence, debris flows are very often reported as floods; whilst flash floods are often reported as mudflows. Clearly this problem can never be solved fully. We have addressed this issue by seeking to include events that would fall under the well-established landslide classification of Cruden and Varnes (1996), which includes debris flows, mudflows and rock falls. In each case the compilers of the database had to make a judgement as to whether the event should be classified as a landslide, using the available reports and, where possible, images of the event.
2. *Definitions of fatalities*. Although in a sense the definition of a fatality might seem straightforward, in the context of a database such as this, it is actually somewhat problematic. First, there is a need to determine whether a death is actually caused by a landslide. This is simple in the case of burial by the landslide or impact from a rock fall. However, should a death that results from a car impacting landslide debris be included? If so, what about the case in which a car is forced to swerve to avoid landslide debris, and ends up driving into the river? Finally, what about the case in which a road is closed by a landslide? As a result vehicular traffic might be forced onto a lower quality road, leading to an enhanced accident rate. Consistency is difficult to achieve in such cases due to the complexity of the natural and social environment. As a general rule, we have worked on the basis that there must be a connection either in a physical sense between the landslide and the individual (i.e., deaths resulting from a car impacting the debris would be included) or in time (so fatalities resulting from a car swerving to avoid a landslide as it impacts a highway would be included, but a car swerving off the road to avoid the debris pile in the following days would not). Clearly the distinction is arbitrary, but is nonetheless necessary. In general, the numbers of fatalities associated with such complex cases is low in comparison with the overall total, meaning that the impact of these concerns is not unduly high.
3. *Secondary hazards*. The issue of the inclusion of secondary hazards is problematic for all database studies. Landslides themselves are often considered to be a secondary hazard associated with storms and earthquakes, which has

resulted in the gross under-reporting of landslide impacts (see Petley et al. 2005a for a review of this topic). However, landslides themselves are also associated with secondary hazards, most notably dam break floods resulting from valley blocking episodes (Costa and Schuster 1991; Dunning et al. 2006). In this study we have sought to include the deaths associated with such secondary hazards within the database where the secondary hazard is naturally occurring (for example, a dam break event). In databases documenting multiple hazard types this can lead to concerns regarding double counting, but this is not a problem when a single hazard type is being studied, as in this study.

4. *Reliability*. Perhaps the greatest concern regards issues of the reliability of the data included in the database. A number of problems arise here:

   a. *Exaggeration and under-estimation*. It is well-established that in large disaster events there is a tendency for local officials and government bodies to exaggerate the death toll (Hittelman et al. 2001 for example). In many cases this is due to double counting of potential victims, or to the inclusion within the list of victims of people who in reality were not in the area. At times it has also been associated with a desire to increase the provision of assistance and/or with corruption. Occasionally, under-estimation may occur, for example where pressures are exerted in order to avoid political embarrassment. Generally, this latter problem is most acute for large events. Additionally, in many cases the death toll includes a number of people who are listed as “missing”. In many cases it is not established how many people in this category have actually died, and there are a range of ways in which final estimates can be derived.
   b. *Post-event mortality.* A further problem lies with the occurrence of deaths days or even weeks after a landslide event. In most cases there is little or no information available as to whether people who are wounded by a landslide eventually succumb to their injuries. Thus, it is reasonable to assume that as a certain proportion of such people do die, the figures within the database are a slight underestimate of the total number of fatalities. Theoretically, it might be possible to apply a correction factor to deal with this issue (perhaps assuming that say 25% of those injured eventually die from their injuries). However, we have no data on what this factor should be in Nepal, so no correction has been applied in this study.
   c. *Small event mortality.* A further problem lies in the inclusion of all events in the study area. In particular, small events with limited numbers of fatalities are often poorly reported, especially where they occur in an area with poor communication infrastructure. It must therefore be accepted that we fail to resolve many of these events, which in some cases might consist of a single piece of rock striking an individual. This lack of resolution is akin to the resolution problem observed when constructing landslide databases from aerial photographs (Stark and Hovius 2001 for example), and it might thus be expected that a similar “roll-over” in the power law frequency distribution of event sizes will be observed. We accept this limitation of our data, but believe that the impact is not as serious as might be feared, as Petley et al. (2005a) demonstrated that for landslides it is the larger events that dominate the fatality statistics.

It could be argued that these limitations mean that the construction and analysis of such a database is questionable. We do not believe that this is the case. In most cases the errors are comparatively small relative to the total number of events and the errors are essentially consistent spatially and temporally through the dataset. At all times these errors must be considered when interpreting the dataset, and we suggest that in general the numbers cited here should be considered to be an underestimate of the total impact of landslides within Nepal.

4 The Nepal landslide dataset

In the complete dataset for the period 1978–2005, we have recorded a total of 397 fatal landslides in Nepal, which caused 2179 recorded fatalities, representing an average of about 78 deaths per year. Analysis of these annual data (Fig. 2) shows that the number of fatalities varies greatly from year to year. The smallest number of deaths occurred in 1981, when only five fatalities were recorded, whereas the largest number was 342 in 2002. A similar variation is noted in the number of fatal landslides per year, which ranges from one in 1981 to 58 in 2002. There appear to be some interesting underlying trends in the data, with distinct periods when the number of fatal landslides and the number of fatalities increase (1982–1989 and 1997–2005) and periods when the numbers are substantially lower (1978–1981 and 1990–1996). It is also notable that there appears to be a general increasing trend, with the five most deadly years all occurring in the period 1998–2005. Note however that this is not a simple upward trend, as a peak in fatalities and numbers of landslides occurred in the period 2001–2003, and a decline is noted thereafter.

A simple examination of the temporal occurrence of fatal landslides reveals the strong climatic control on the triggering of instability (Fig. 3). There are no recorded landslide fatalities in the period from November to April, reflecting the very dry conditions in Nepal during this part of the year. A small number of events have been recorded for May, with a further increase in June. Interestingly, there is a marked

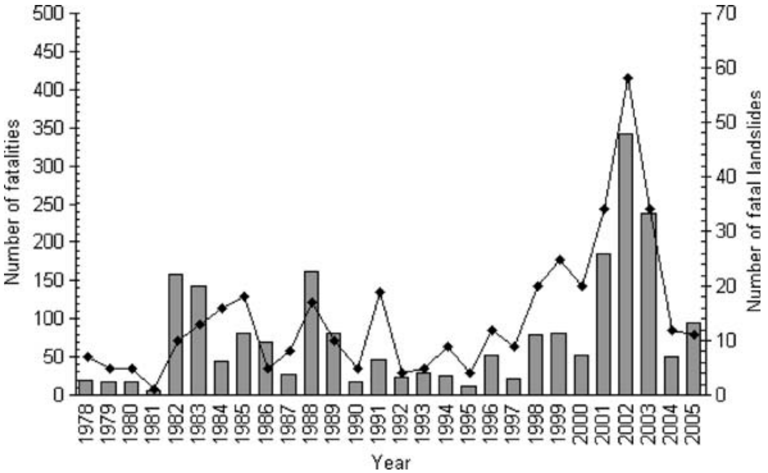

Fig. 2 Graph showing the number of landslide fatalities (bar graph, left hand scale) and the number of fatal landslides (line graph, right hand scale) each year for the period 1978–2005 for Nepal

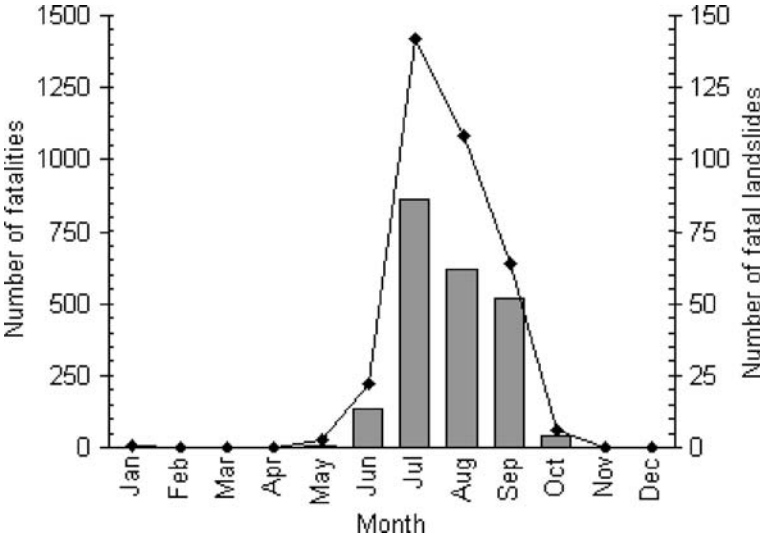

Fig. 3 Graph showing the occurrence of landslide fatalities (bar graph, left hand scale) and the number of fatal landslides (line graph, right hand scale) by month for the period 1978–2005 for Nepal

peak in landslide occurrence in July, with slightly lower but still notable totals in August and September. The number of landslides declines to a very low number in October, and to zero in November. This very strong seasonality reflects the occurrence of rain associated with the South Asian Summer Monsoon, which in Nepal has a modal start date of 10 June, peaks in terms of rainfall intensity in July and continues to a modal date of 21 September (Hannah et al. 2005). This main monsoon period is characterised by a moisture-laden air mass that moves progressively northwards from the Bay of Bengal. The pre-monsoonal period extends from March to May, and is characterised by warm, dry weather with limited rainfall. The post-monsoon period (October to November) is dry and warm, with November being the driest month on average. Finally, the winter period (December to February) is generally dry and cool. Thus, it is clear that the annual occurrence of landslides depends heavily upon the summer monsoon. Interestingly however, although the monsoon period represents 60–80% of the annual total precipitation, and 55–80% of runoff (Shrestha et al. 2000), it accounts for 92% of landslide fatalities and 90% of the fatal landslides.

The distribution of fatal landslides across Nepal is very uneven (Fig. 4A). In general, the density of fatal landslides is low for the Terai districts and for the mountain districts in the northwest of the country (Fig. 1). The density is highest for the hill districts, especially in the central and eastern parts of the country. There is also an area of higher density in the hill districts in the west of Nepal. This distribution appears to be determined primarily by a combination of relief and precipitation. The Terai districts mostly comprise flat plains, upon which landslides are not common. In the hill and mountain districts the distribution reflects reasonably well the distribution of annual precipitation totals, for which the highest levels are in the hill districts, especially in central and eastern Nepal (Fig. 4B).

Many authors have suggested that the frequency–area relationship for medium and large landslides can be described by an inverse power law relationship (Hovius

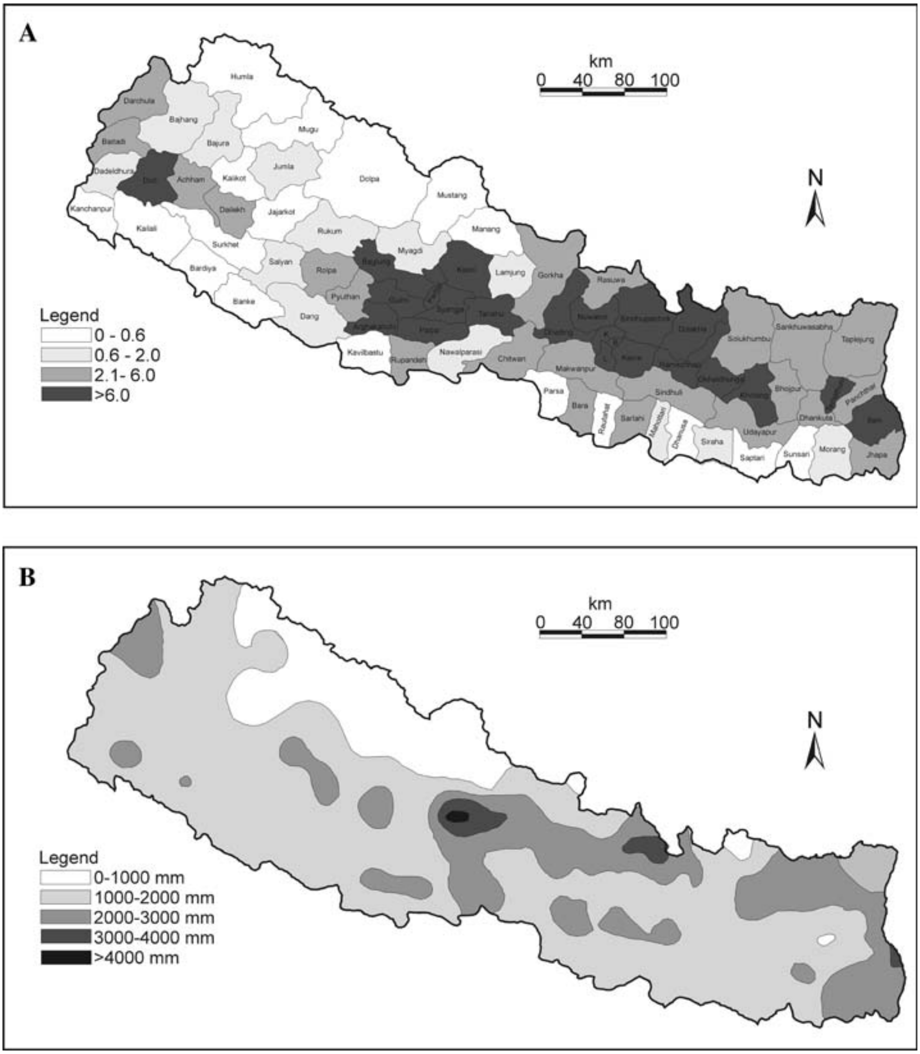

Fig. 4 (**A**) The distribution of fatal landslides by district for Nepal. The data are given as the recorded number of fatal landslides per 10^3 km^2 for the period 1978–2005. (**B**) The corresponding annual precipitation variability (data from Chalise et al. 1996)

et al. 1997, 2000; Dussauge et al. 2003; Malamud et al. 2004). This relationship appears to hold despite large variations in landslide type, size, and triggering mechanism (Malamud et al. 2004). We have undertaken this type of analysis for the landslide fatality dataset, in which we use fatalities as the indicator of landslide size. For events with higher numbers of fatalities a power law "tail" is present (Fig. 5), although note that this is across just three orders of magnitude of size, whereas the more commonly analysed power law frequency–landslide area relationships extend over five or even six orders of magnitude (Turcotte 1999). This reduced size power law tail is probably due to a limitation of the current dataset given the constraints on the measure of landslide size using fatality data. It is likely that a larger dataset

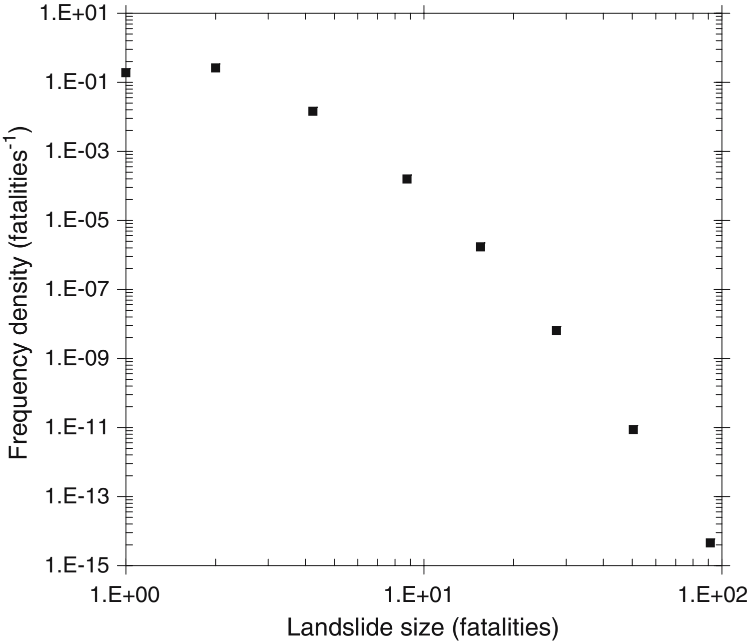

Fig. 5 The Nepal landslide dataset plotted as a probability density function

would show the same pattern over a greater number of orders of magnitude. For smaller events (i.e., those with ten or less fatalities) a "roll-over" is apparent in which the power law no longer applies, as seen in frequency-area data of Malamud et al. (2004). Such roll-overs have been considered to be more than just an artefact of data collection, representing a real characteristic of landslides (Malamud et al. 2004). However, Stark and Hovius (2001) suggested that at least in part it might be the result of under-sampling of smaller events due to problems associated with mapping resolution. In the case of the landslide database we consider that it is likely that this roll-over is also a real attribute of the landslide distribution. However, it may also be that there is significant under-sampling of the dataset as it is most likely that the smallest landslides, which might kill only one or two people, might not be reported, especially in rural areas. The largest landslides on the other hand are much more likely to be documented, and thus to appear in the dataset. What is clear is that for Nepal landslide fatalities show the same general frequency–magnitude relationship as for the landslide sizes themselves.

5 Causation in the temporal variation of landslide fatalities in Nepal

Clearly there is considerable variation in the temporal occurrence of landslides in Nepal, with an apparent underlying cyclicity with time. Here we seek to examine these trends and to attempt to account for them. To do this we use the running mean technique common in hydrology and climatology (Horii and Hanawa 2004 for example), based on a five–year kernel, in order to smooth both the climate and fatality data. This permits the analysis of trends in the dataset to be undertaken easily.

It is clear that the majority of fatal landslides in Nepal are triggered by monsoon rainfall. A number of indicators are commonly used to examine monsoon strength, based on either precipitation intensities or on atmospheric circulation. The most widely-used indicator of the former is the All India Monsoon Rainfall Index (AIMI), which is an areal average of 29 subdivisional rainfall datasets (Parthasarathy et al. 1995) based on total rainfall across 306 rainfall stations that span India, although it should be noted that few if any of these are located in the Himalayas. The index is based upon rainfall totals for June, July, August and September. AIMI data for the period 1978–2005 have been obtained from the Indian Institute of Tropical Meteorology.

The five year running mean of landslide fatalities shows the trends described previously, with comparative peaks in 1982–4 and 2001–3, and a trough in 1992–5 (Fig. 6). Notably, the peak in 2001–3 is substantially greater than in 1982–4. Broadly speaking, the AIMI shows the same trend, but in reciprocal form (Fig. 6). This comparatively weak but still significant, linear, inverse relationship is evident in regression (Fig. 7). In many ways this is counter-intuitive as it suggests that more fatalities occur in dry years than in wet ones. However, in a comparison of annual (rather than monsoonal) rainfall trends between Nepal and India for the period 1959–1994, Shrestha et al. (2000) noted that "*a comparison between precipitation fluctuations over Nepal and over India does not show good agreement*". This may suggest that the AIMI data are a poor indicator of monsoon strength for Nepal on account of the different spatial coverage. Indeed the same authors noted that:

> "the precipitation climatology in the northern part of the subcontinent (including the Himalayan region) is different from the rest of the subcontinent, and that the precipitation record from India as a whole (and generally excluding the Himalayan region) is not always a suitable representation for the region".

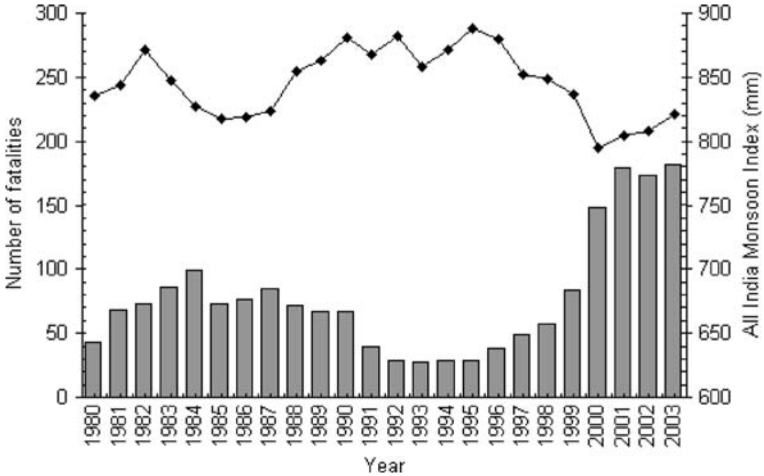

Fig. 6 Five-year running means, indicating medium term trends, for the number of fatalities per annum (bar graph, left axis) and AIMI (line graph, right axis)

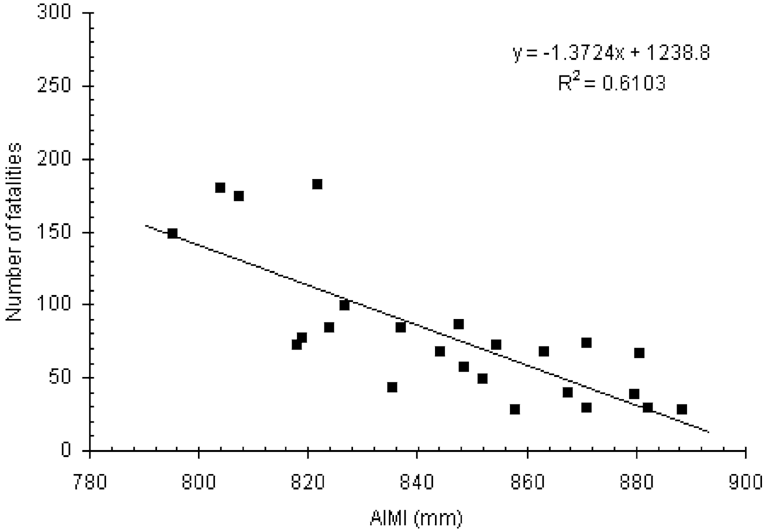

Fig. 7 Regression between the number of fatalities per year and AIMI, based on five-year running mean data

However, they did not observe an inverse relationship between monsoon precipitation in India and Nepal as our data might infer. Shrestha et al. (2000) did note that there is an eleven year periodicity in the Nepal annual precipitation record, which they related to sunspot cycles. The landslide data suggest a rather longer (ca. 14-year) periodicity, however.

An alternative index of monsoon strength is the new South Asian Summer Monsoon Index (SASMI) of Li and Zeng (2003). This index is based upon a dynamical normalized seasonality index of intensity of the wind field at the 850 hPa level. As such it is not an indicator of the intensity of monsoon precipitation, but nonetheless it provides an index of the strength of the atmospheric processes that are responsible for rainfall generation. As with the AIMI dataset, there appears to be an inverse relationship between the overall strength of the monsoon as indicated by smoothed SASMI data and the number of landslide fatalities (Fig. 8). Regression of the two datasets suggests that this is rather a complex relationship in reality, as the data appear to plot into two distinct groups (Fig. 9). During the period 1980–1994 there is a simple, but comparatively weak linear relationship between the numbers of landslide fatalities. From about 1995 the relationship appears to change, with a much larger number of fatalities for a given SASMI value. The relationship remains strongly linear. Thus, there appears to be a change in some way in the dynamic relationship between the number of fatal landslides and the SASMI. We return to this issue below.

The inverse relationship between the monsoon indices and the number of fatal landslides appears to be counter-intuitive. However, Shrestha et al. (2000) compiled an index of monsoon precipitation for Nepal for the period 1959–1994, broken down into the east and the west of the country, and the Terai, hill and mountain districts. We have aggregated the index for the hill districts east and west and compared this with the SASMI, using the running means for the period 1978–1994 (Fig. 10). This shows a strong, linear, negative relationship between the SASMI and the Hill Districts monsoon precipitation, which would appear to explain this anomaly. Thus,

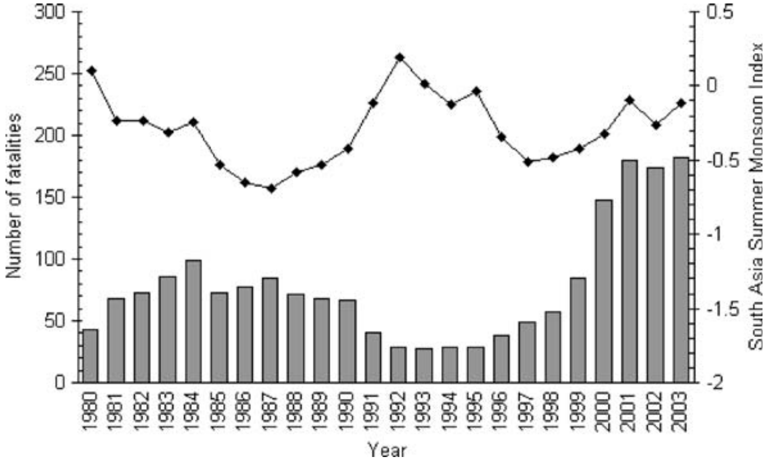

Fig. 8 Five-year running means, indicating medium term trends, for the number of fatalities per annum (bar graph, left axis) and the July SASMI (line graph, right axis)

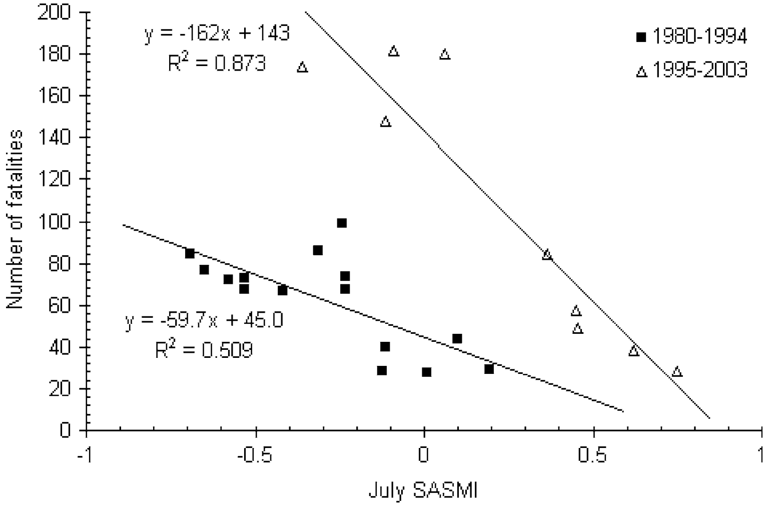

Fig. 9 Regression between the number of fatalities per year and the July SASMI, based on five-year running mean data. The data are divided into two populations, 1980–1994 and 1995–2003 as different relationships between appear to operate for the two sets

when the monsoon index is strongly positive, the total monsoon precipitation in the hill districts of Nepal is comparatively low and vice-versa. Thus, the inverse relationship between SASMI and the number of landslide fatalities is explicable, suggesting that a prediction of the likely value of SASMI would allow an indication of the intensity of landslides triggered by the monsoon. The net impact of precipitation is thus intuitive and logical. In years in which the monsoon indices are high and thus the monsoon is intense, the precipitation level reaching the Middle Hills region is low, and thus comparatively few landslides occur. On the other hand, in years when the monsoon indices indicate a weak monsoon, the level of precipitation is high in the Middle Hills region, and the occurrence of landslides is consequently high.

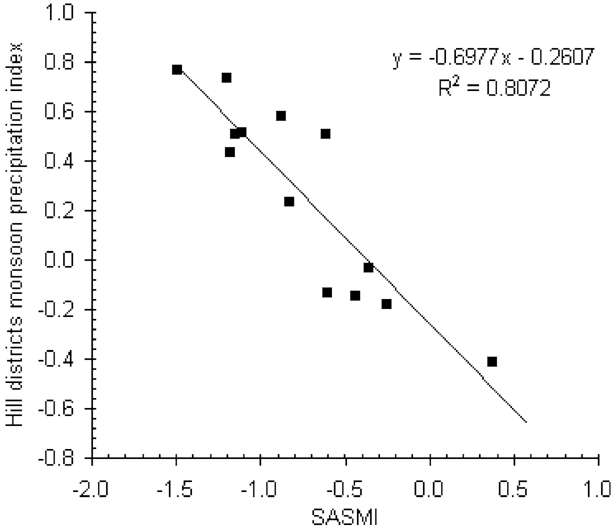

Fig. 10 Regression between the Hill districts monsoon precipitation index, as derived from Shrestha et al. 2000, and the SASMI for 1978–1994, showing a strong, linear, inverse relationship

Bookhagen et al. (2005) noted that the pattern of rainfall associated with the summer monsoon in the Himalayas is affected by both the regional scale atmospheric conditions and the more local scale effects of topography, most notably the interaction between the terrain and the wind distribution. The landslide dataset clearly supports this view.

The cause of the increased prevalence of landslide fatalities is of key importance to the management of the hazard in Nepal. Examination of the relationship between average landslide size and the SASMI indicates that there is a strong linear relationship (Fig. 11). It is notable that the average landslide size increases when the

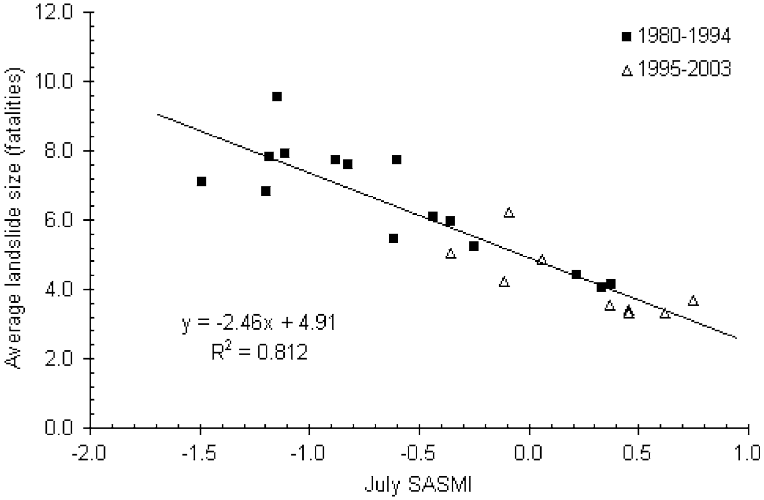

Fig. 11 Regression between the average size of the landslides, and the July SASMI, showing a strong, linear, inverse relationship

SASMI reduces, i.e. when the precipitation total increases. It is perhaps logical that larger rainfall events trigger greater numbers of large landslides. Interestingly however, this relationship is constant through time and does not show the large increase in recent years seen in the total number of fatalities. It is clear that change appears to be one of an increase in the number of fatal landslides occurring, each of which kills on average similar numbers to before, rather than there being the same number of fatal landslides, each of which is larger.

This would seem to imply that there is an increase in either the susceptibility of the landscape system to rainfall events—i.e., that each for a rainfall event of a given size more landslides occur; or a change in the vulnerability of people—i.e., the same number of landslides are occurring, but there are more people in the way of them. However, if the change was due to increased vulnerability due for example to increased population densities, then it is surprising that the average size of the events has not increased—it is logical that there would be more people in the path of each fatal landslide, which should increase the overall average. Thus, it seems likely that there is an increased number of landslides occurring in the landscape with time. It appears that the change in occurrence of landslides is dated from about 1995, after which quite an abrupt transition has been noted. We do not believe that this is solely the result of increased reporting of landslides as there is no logical reason why such an abrupt change should be noted at this time, and we would expect that increased reporting would lead to more of the smaller events being noted, i.e., the average size in terms of fatalities should decrease.

One logical explanation might be the effect of deforestation in Nepal. Deforestation is widely recognised as a significant cause of landslides in upland environments (Glade 2003 for example), and especially in Nepal (Gerrard and Gardner 2002). Rates of deforestation in Nepal are high, averaging 1.35% of the forest resource per annum in 2005 (FAO 2005) (Fig. 12A). However, the rate of deforestation peaked in the period 1985–1990 (Fig. 12A), and has declined subsequently. Thus, the more recent large increase in the occurrence of fatal landslides does not appear to coincide with the main phase of deforestation, although a lag effect and the role of a critical threshold in forest cover, at which point the occurrence of landslides increases dramatically, cannot be discounted. Indeed it is difficult to imagine that this level of deforestation is not a contributor to this substantially increased occurrence of fatal landslides.

A second potential explanation lies in the rapid development since about 1990 in the road network of Nepal (Fig. 12B). This results from a change in national and international priorities for the economic and social development of the country in which an emphasis has been placed on “access” for rural communities, with a key aspect of this being the construction of a new and extensive network of low technology rural roads. Thus, most of the roads built since 1990 have been gravel or earthen roads, constructed using the participatory approach (i.e., using local human and physical resources as much as possible) and with comparatively low levels of conventional engineering design input. The increased occurrence of landslides along new road corridors is very well documented (Sidle et al. 2006 for example). In addition, the construction of new roads may cause changes in the dynamics of local societies as economic activity restructures to take advantage of the new opportunities presented by the road. Thus, in many cases there is a relocation of the population to live beside the road, which might lead to increased vulnerability and

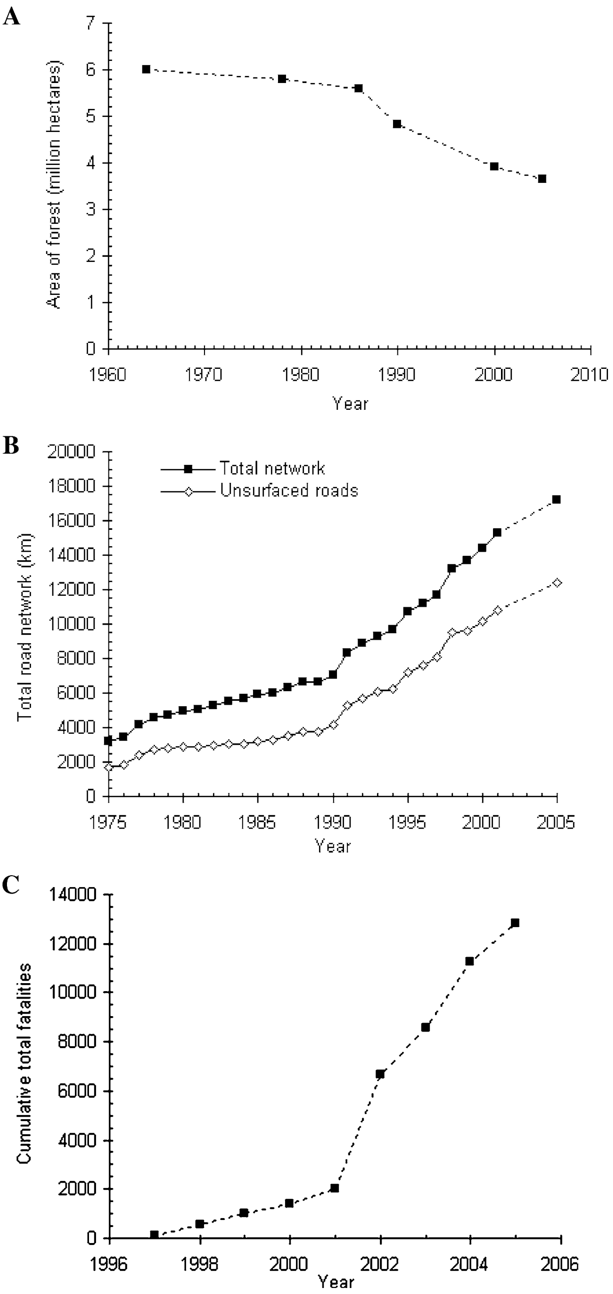

Fig. 12 Three possible trends causing the increased sensitivity of the landscape to landslides. (**A**) The effects of deforestation (after Govil 2000), (**B**) The growth of the road network in Nepal, illustrating the dramatic increase in the amount of road construction in the early part of the 1990's, (**C**) The number of fatalities per annum associated with the ongoing civil war

changes in land use, including in some cases the abandonment of the terrace cultivation systems. These changes might well lead to an increase in landslide impacts.

Finally, it is notable that the changes coincide with the initiation of the ongoing civil war in Nepal (Fig. 12C). It is possible that this destructive conflict is increasing vulnerability due to enhanced levels of poverty and the consequent migration of people from the Maoist controlled rural areas into the government controlled major

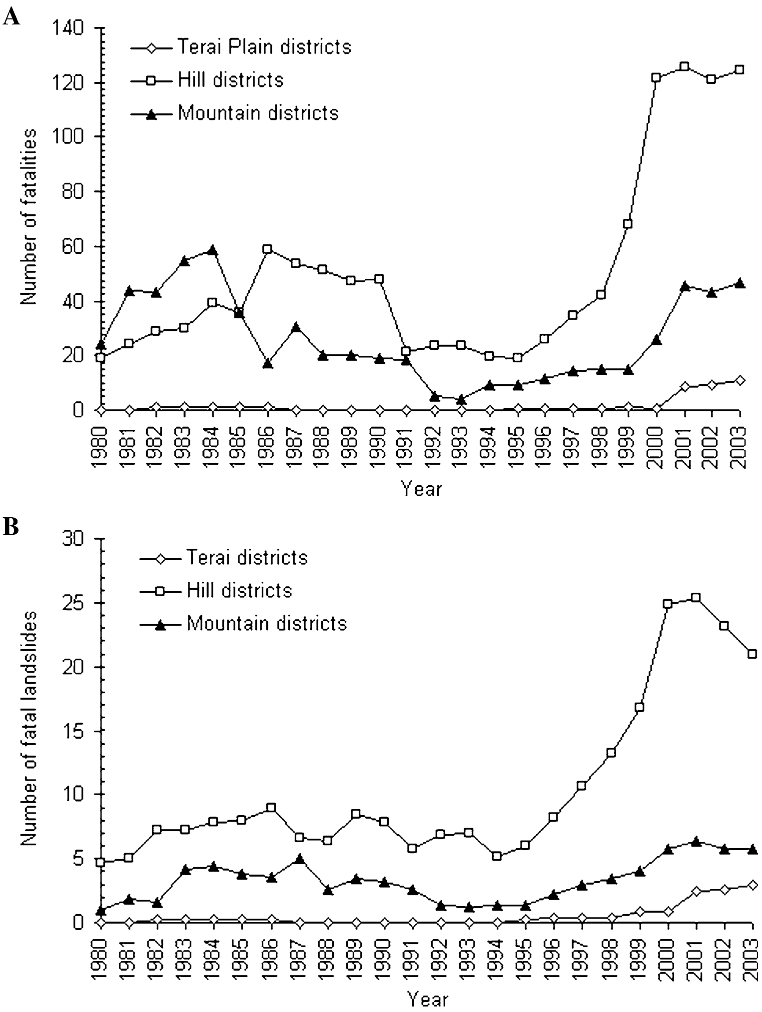

Fig. 13 Graph showing the change across the three main terrain areas of Nepal in (**A**) the number of landslide fatalities and (**B**) the number of fatal landslides per year. Both datasets have been smoothed using the five-year running mean

population centres, especially on the Terai plain. The growth of landslide-prone urban slums has been a consequence of this process in other countries (Barling 2001 for example), and so might also be significant in Nepal.

An insight into the role of these three processes is given by an analysis of the number of both fatalities (Fig. 13A) and fatal landslides (Fig. 13B) according to the three main terrain units. It is clear that there has been only a small increase in the number of both fatalities and fatal landslides in the Terai plain areas. Thus, it seems unlikely that the large increase in the number of fatal landslides is due to this population migration. Indeed, most of the changes have occurred in the hill districts. Interestingly, Joshi (1998) suggested that deforestation in the hill districts of Nepal, whilst not insignificant, has not increased in rate in the 1990's. Most of the deforestation during this time has occurred on the Terai plains. Thus, it does not appear likely that deforestation is the major cause of this increase in fatal landslide occurrence, although it is probably a small component. On the other hand, the hill districts have been the main focus of road building activity since the mid 1990s. Thus, the most likely explanation for the increase in landslide activity would seem to be the road construction programme, and the associated changes that this causes. Needless to say there is an urgent need to examine this in more detail.

6 Discussion

In this study we have examined the occurrence of fatal landslides in Nepal in the period 1978–2005 through the compilation of a database of fatal landslide events. Of course we fully recognise the deficiencies of such approach, as outlined at the start of the article. We recognise that the error levels in the data are quite large, and that in general the database probably underestimates the impact of landslides. There is undoubtedly one major additional error in the database. This is the result of a major flood and debris flow disaster that struck southern and central Nepal on 19th–22nd July 1993 as a result of an extreme rainfall (cloudburst) event. This event represents the largest non-seismically-induced disaster in the historic record for Nepal. About 70,000 people in total were affected by this disaster and the death toll exceeded 1,160 in the Bagmati, Kulekhani and Narayani basins. A proportion of these fatalities, 160 of which occurred in upland areas, were the result of landslides. Unfortunately however, we have not been able to discriminate between those fatalities caused by floods and those caused by landslides in this event. It is likely that the majority were caused by true river flood events, but it is also likely that tens to hundreds of deaths were caused by landslides. Unfortunately it is likely that we will never be able to resolve this issue. It is also notable that the ongoing dataset on disasters in Nepal, collated independently from our project by the authorities, does not discriminate between floods and landslides even now.

Despite that underestimation of the true impact of landslides in Nepal, we believe that the study reported here yields very interesting information. Notably the database suggests that the occurrence of landslides in Nepal is heavily cyclical, with the cyclicity being dependent upon the variability of the strength of the monsoon. In general it appears that years with strong atmospheric monsoonal conditions are associated with lower numbers of landslide and vice-versa. This seems to concur with an inverse relationship between rainfall patterns in the hill districts of Nepal and the monsoon strength.

The research presented here highlights two issues associated with the triggering of landslides in the Himalayas. First, it is clear that in general the control on the annual occurrence of landslides is the stage of the cycle of monsoon strength. However, on a more local scale, as the 1993 event described above illustrates, many of the landslides themselves are triggered by highly localised extreme precipitation events (cloudbursts). In any given year the number of cloudburst events is probably small, and their impact is spatially limited. Thus, whilst it is possible to state that for a given part of the monsoon cycle a given level of landsliding can be expected, the actual locations of the landslides cannot be determined. Thus, such a study is useful for understanding trends and for forecasting overall impacts, but not for predicting the actual location of events in time and space.

Our data suggest that the occurrence of fatal landslides in Nepal has increased in recent years, and that the level of this increase is greater than would be expected from the natural cyclicity. This increase appears to have occurred primarily in the hill districts of Nepal, but has not led to a change in the number of fatalities per event over and above the normal fluctuation. This suggests that the landscape has become more susceptible to landslides, and we hypothesise that the most likely explanation for this is the rural road-building programme, which coincides with this increase. The effects of deforestation are probably also significant, but the impact is probably lower than might perhaps be expected. There do not appear to be substantial changes in the rainfall pattern occurring at the present time (see for example Nayava 2004), which would preclude climate change effects.

Thus, it would appear that the change in policy in terms of the construction of roads, which is driven at least in part by overseas donor agencies, is leading to increased landslide impacts. This is in agreement with the findings of Sidle et al. (2006), who demonstrated that the density of landslides associated with road construction in mountainous terrains is one and in some cases two orders of magnitude greater than for other land use changes. In Nepal, a remarkably large programme of road construction in (comparatively) high mountain terrain with a climate characterised by seasonal, intense precipitation is underway. In many cases in tectonically active areas, such as the Himalayas, large numbers of slopes are a state of incipient failure (see Petley et al. 2005c for example). In an undisturbed system the trigger for failure would probably be a very large precipitation event (for example a cloudburst) or a seismic shock (see Murphy et al. 2002; Sepulveda et al. 2005; Chen and Petley 2005; Lin et al. 2006 for example). It seems likely that poorly-engineered road construction in effect reduces the size of a potential trigger process, resulting in extensive, large-scale landsliding along the alignment. The resulting impacts are documented in the data presented here.

Whilst the philosophy behind rural access programmes is probably sound, it would appear that better selection of road alignments, enhanced site investigation and increased engineering design would greatly benefit the communities involved. It is an old adage that it is harder to stop a landslide than it is to start one. Thus, it is likely that at least some of the roads constructed under this approach will cause substantial environmental degradation and increased levels of risk for years to come. Future roads should be designed to minimise these impacts.

7 Conclusions

In this study we have examined in detail a large dataset on the occurrence of landslide-induced fatalities in the period 1978–2005. Our data suggest that as Hewitt (1997) proposed, landslides are probably underrepresented as a hazard in mountain environments. They cause a comparatively large numbers of fatalities in Nepal, with most of the landslide deaths in that country being concentrated in the hill districts of the Middle Himalayas. Our data suggest that the impact of landslides is increasing with time, but is strongly controlled by variations in the strength of the monsoon. Interestingly, the relationship shows that when the summer SW Asian monsoon is intense the number of fatalities is low and vice-versa. Whilst this is counter-intuitive, there is now ample evidence that the controlling processes on precipitation in the mountain areas are dominated by the interactions between topography and medium scale airflow patterns (Bookhagen et al. 2005). Thus, the monsoon conditions change the distribution of precipitation on a regional scale such that in years in which the region-wide monsoon is weak, the level of rainfall, and thus the occurrence of landslides is low. Within this pattern, however, there is a strong increasing trend in the number of fatalities occurring in Nepal at any point in the monsoon cycle. Whilst the cause of this increase is not clear, we hypothesise that this may be associated with the ongoing road construction programme in Nepal as well as the effects of deforestation and population changes. If this is indeed shown to be the case then there may be a pressing need to amend the design of rural access development projects in Nepal and many other less developed areas.

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