The analysis of the spatial patterns and controls governing the global occurrence of fatal landslides

Katie Jane Oven

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The Analysis of the Spatial Patterns and Controls Governing the Global Occurrence of Fatal Landslides

Katie Jane Oven

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Department of Geography
Durham University

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Declaration

This thesis is the result of my own work. Data from other authors contained herein are acknowledged at the appropriate point in the text.

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ABSTRACT

In the research presented here, a global inventory of fatal landslides has been generated allowing the investigation of the spatial distribution and temporal occurrence of mass movement events. There are important regional differences within these data with Asian fatalities being characterised by high frequency, low magnitude landslide events. In comparison, high magnitude events were found to be responsible for the high fatality totals in the Americas. This research has demonstrated that the spatial distribution of fatal landslides is best explained by a combination of physical and social factors and has yielded some interesting results.

87% of the fatal landslide events recorded within the database were triggered by high intensity of prolonged rainfall events associated with tropical cyclones or monsoon rainfall that are compounded in areas of high relief associated with tectonically active mountain belts. Increasing landslide impacts are often associated with less developed countries, where there is rising population density, rural to urban migration, growth of megacities, and severe land degradation. However, the results indicate that the occurrence of landslide fatalities are not simply a function of level of development of a country or population density but that fatalities predominantly occur within middle income countries and rural areas which are increasingly vulnerable to landslide disasters. This can be attributed to changes in physical systems, most notably climate variation.

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ABBRIEVIATIONS

The following abbreviations have been referred to within this thesis:

CIESIN	Centre for International Earth Science Information Network
CRED	Centre for Research on the Epidemiology of Disasters
GCO	Geotechnical Control Office, Hong Kong
IFRCRCS	International Federation of Red Cross and Red Crescent Societies
IITM	Indian Institute of Tropical Meteorology
ILC	International Landslide Centre, Durham University
NCDC	National Climatic Data Centre
NCDR	National Science and Technology Centre for Disaster Reduction
NGDC	National Geophysical Data Centre
NOAA	National Oceanic and Atmospheric Administration
OCHA	United Nations Office for the Coordination of Humanitarian Affairs
POPIN	The United Nations Population Information Network
UNEP	United Nations Environment Programme
USGS	United States Geological Survey

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1 INTRODUCTION AND PROJECT RATIONALE

The *'impact of landslides in the world is considerable, though not well known'*.

(Brabb, 1989:VIII)

1.1 Introduction

Landslides are one of the most destructive geological processes and are a major cause of loss of life and economic damage (Brabb, 1993). For example, in 2004 there were more than 7,000 fatalities from landslides worldwide (ILC, *pers comm.*). Major disasters included Haiti, where torrential rains from Hurricanes Jeanne and Ivan triggered extensive landsliding causing >3,000 fatalities (UNEP/OCHA, 2004) and the Philippines where >1,000 people were killed by typhoon-triggered mudslides (IFRC, 2004).

Figure 1.1 shows the number of fatal landslide events and the number of landslide related deaths recorded per year between 1975 and 2004 by the Centre for Research on the Epidemiology of Disasters (CRED) which reported an average of 530 fatalities per year, with ~350 fatalities recorded for 2004. There is clearly a discrepancy between the total figures recorded by the International Landslide Centre (ILC) and CRED which raises a number of questions regarding the global occurrence of fatal landslide events.

The data also shows an overall increase in the number of fatal landslides and associated fatalities between 1975 and 2004 (figure 1.1). Initially, the most obvious explanation for the rising occurrence of fatal landslides is an increase in the level of geological and meteorological activity triggering mass movement, which is in conflict with the general acceptance that long-term frequency of natural events has remained more or less constant (Chapman, 1994; Uitto, 1998). The increase in the impact of landslide activity has therefore been ascribed to human and social factors, rather than to changes in the physical systems. For example, increasing landslide impacts are largely associated with less developed countries, deforestation, changes in farming practices and rising population densities (Hewitt, 1997; Alcántara-Ayala, 2002). However, and perhaps surprisingly, this is largely based on anecdotal evidence with limited, if any, empirical data to justify these observations.

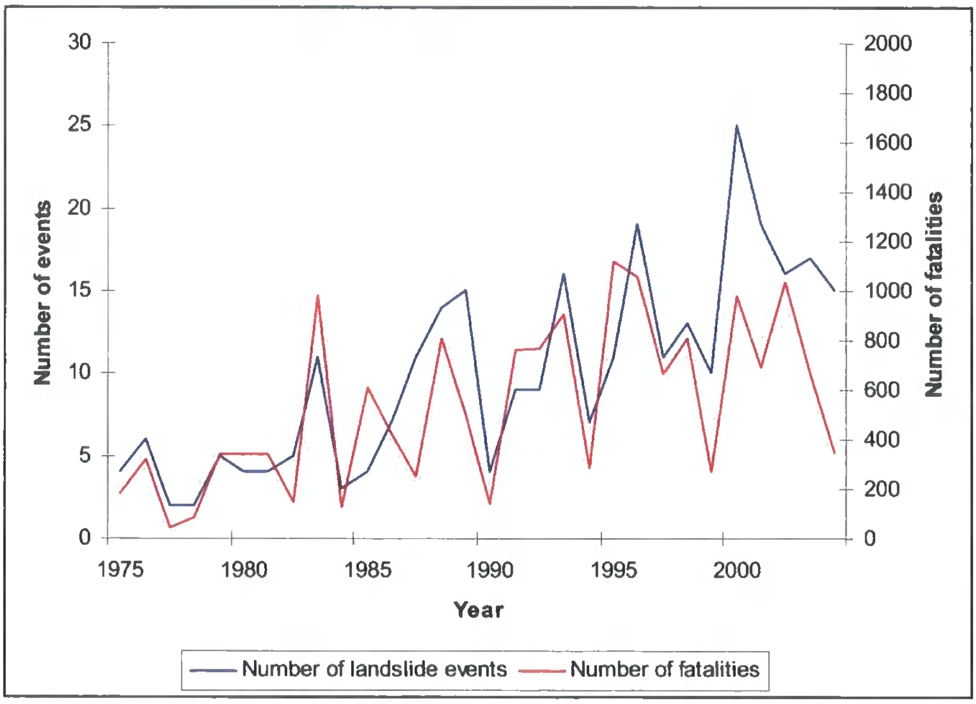


Figure 1.1 The number of landslide disasters and landslide related deaths recorded between 1975-2004 (adapted from EM-DAT – OFDA/CRED International Disaster Database, 2005).

1.2 Research context

As part of the International Decade of Natural Disaster Reduction (1990s), the International Geotechnical Societies UNESCO Working Party on mass movement proposed a world inventory of landslide events (Brabb, 1993; Guzzetti *et al*, 1994 and UNESCO, 1990). It was recognised that compiling a detailed inventory and mapping and analysing the occurrence of groups of landslides globally, would enable the identification of the broader processes active over a number of sites that contribute to slope movement (Cruden and Brown, 1991). However, despite an encouraging start, there are no evident outputs and the project appears to be stillborn.

Focusing on landslide fatality data specifically, Guzzetti (2000) undertook a brief analysis of the available information. The report concluded that while a substantial volume of literature has been published, few data on the total number of fatalities and the average number of deaths per year are available. In addition, it was felt that the figures reported were largely incomplete and misleading. Preliminary studies suggest these data underestimate the impact of landslide activity, with many low magnitude fatal landslide events, particularly in rural areas going unreported. Landslide fatalities are often reported as the result of the processes inducing the slope failure for example, earthquakes and high intensity precipitation events, rather than being attributed to landslide activity *per se* (Jones, 1992).

1.3 The International Landslide Centre database

The International Landslide Centre at Durham University has compiled an inventory of fatal landslide events from 1900 to the present day, with a more detailed inventory from

2002. While it is recognised that there are flaws in using fatality data as an indicator of landslide activity, this research suggests that such data is reasonably reliably recorded, even in remote areas and less developed countries, providing a relatively reliable and spatially consistent dataset for analysis (Petley *et al*, 2005).

The archive records >1500 landslides including soil/rock failures in the form of slides, flows, falls and debris flows, where these can be clearly differentiated from flood events. Data are collected on a daily basis from sources including newswire reports, academic papers, government data and aid agency reports. The key information extracted includes the date, location (national, regional and local), landslide type, size, the triggering mechanism, the number of fatalities, the number of people injured, the number of people reported missing, details concerning the landslide impact and the source of the information. However, prior to the undertaking of this study limited analysis of the compiled database had been undertaken.

1.4 Taiwan

While the research undertaken primarily focused on the global scale, Taiwan was selected as a case study to evaluate the quality and completeness of the database and to address issues of location precision. Taiwan is highly susceptible to landsliding and as a result many disasters occur annually. The island was therefore a statistically viable case study for investigation with relatively robust landslide datasets available for analysis.

In many respects Taiwan is a-typical in relation to global landslide activity:

- The land mass is seismically active.

Taiwan sits on an active fault between the Philippine Sea plate and the Eurasian continental plate (Wang and Burnett, 1990) making the land mass seismically active (figure 1.2). Many landslides are triggered by earthquake events (Chang, 1996), for example, the 1999 Chi-chi earthquake triggered approximately 10,000 mass movements across the island (Wang *et al*, 2003).

- Taiwan is characterised by mountain terrain.

Approximately 70% of the island is comprised of upland areas (Hung *et al*, 2002).

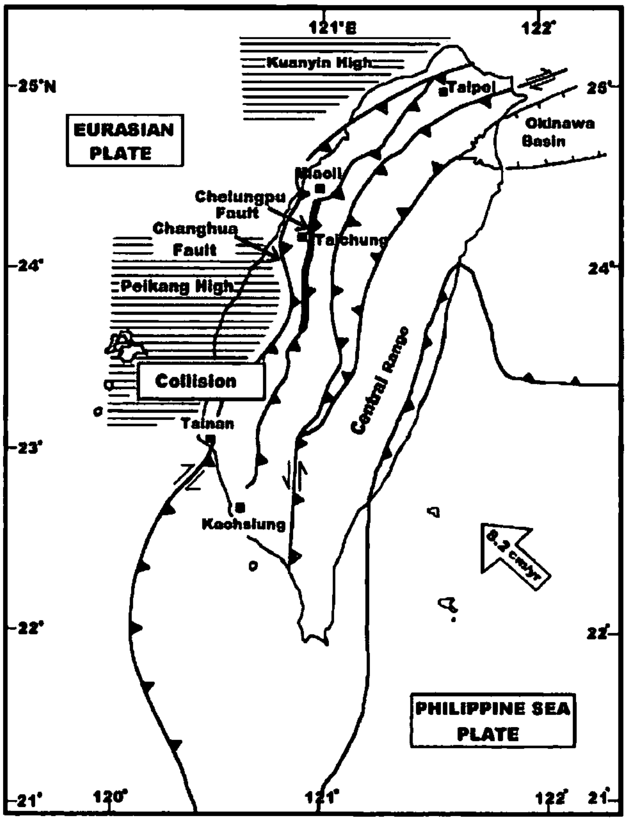


Figure 1.2 The tectonic and structural setting of Taiwan (Shou and Wang, 2003 adapted from the Central Geological Survey of Taiwan, 1986; Lacombe *et al*, 1999). The large arrow shows the direction of convergence of the Philippine Sea Plate and the heavy lines correspond to the major thrust faults.

- Taiwan is associated with high precipitation inputs.

  The island is located in the subtropics, with an annual precipitation of >2000 mm due to the high frequency of typhoons. Landslides are commonly induced by rainstorms associated with these typhoon events (Hung *et al*, 2002); for example, in 2001 typhoon Toraji triggered widespread landsliding in the central and eastern regions (Wang *et al*, 2003).

1.5 Research objectives

The aim of the research was to analyse the spatial patterns and controls governing the global occurrence of fatal landslides. This was explored through four detailed research objectives outlined below.

1. *To create a workable database from the existing long term inventory compiled by the International Landslide Centre.*

   The ILC database was compiled to provide a record of fatal landslide occurrence; however the quality of the data and the completeness of the catalogue varied considerably throughout. An attempt was made to enhance the existing database using a range of sources including online media information, aid agency and NGO reports and scientific literature. Where possible dates, locational information and fatality data were cross checked between a number of sources to increase the reliability of the dataset.

2. *To map the distribution of landslides to create a global spatial landslide inventory.*

   A spatial inventory in the form of a digital map was created from the global landslide data set using GIS (Geographical Information System) software. GIS enables the effective management of the large volume of complex, spatial data held within the landslide database. To enable the mapping of the landslides, the events were first located and spatially referenced, with the latitude and longitude determined for each individual landslide event.

3. *To investigate the spatial distribution of landslides in relation to potential human and physical causative factors.*

   A series of data sets based upon a range of human and physical causative factors were integrated with the spatial landslide data. GIS was used to present and manipulate this information in the form of layers, enabling extensive digital and qualitative analysis of the spatial relationship between fatal landslides and their causative factors. Both spatial and temporal analysis was undertaken and this involved analysing the spatial distribution patterns on a sub-regional, regional and global scale.

4. *To evaluate the completeness of the landslide database.*

   An attempt was made to evaluate the completeness of the ILC landslide database. Comparisons were firstly made with other established global landslide fatality datasets including the EM-DAT Disaster Events Database compiled by the Centre for Research on the Epidemiology of Disasters, University of Louvain, Belgium and the global inventory compiled by Alexander (2005). Fieldwork was also undertaken in Taiwan and a link established with the National Taiwan University in Taipei, with the aim of analysing Taiwan's national landslide inventory in relation to the global landslide database.

2 REVIEW OF THE LITERATURE

2.1 Introduction

The literature review has been divided into sub-sections reflecting the interdisciplinary nature of the research being undertaken. Sections 2.2 and 2.3 address issues concerning data collection and disaster statistics followed by a critique of existing studies that have attempted to analyse the spatial and temporal trends in landslide hazard occurrence. Sections 2.4 and 2.5 examine the physical and human causative factors and triggering mechanisms of landslide activity.

2.2 Assimilating and analysing landslide fatality data: a review of the literature

In order to undertake a comprehensive analysis of the global distribution of landslide fatalities, there is a requirement for reliable data at the global scale. Although a substantial volume of literature on landslide fatalities has been published (for example, Alexander, 1989, 2005; Guzzetti, 2000; Brabb and Harrod, 1989) there are significant variations in the number of deaths recorded. This may be attributed to the difficulties in recording landslide events in rural areas with landslide impacts often masked by association with large-scale geophysical processes such as hurricanes and floods (Brabb, 1993). Thus, landslide fatalities are often ascribed as being the result of processes inducing the slope failure (an earthquake or typhoon for example) rather than being attributed to landslide activity (Jones, 1992). These findings all suggest that the hazards posed by landslides are far greater than the level implied by most existing datasets.

2.2.1 National databases

Many countries including France (Flageollet, 1994), New Zealand (Glade and Crozier, 1996) and the United Kingdom (Brunsden and Ibsen, 1994) have established national landslide inventories. Elsewhere, more detailed databases for specific regions have been compiled, such as Hong Kong (Wong and Hansen, 1995), the USA (Brabb, 1989) and Germany (Jäger and Dikau, 1994). There is certainly potential to amalgamate these individual databases with a view to creating a global inventory. Glade and Crozier (2005) compiled a detailed list of information sources on spatial landslide distribution and inventories for different regions worldwide, highlighting the number of spatial landslide studies that have been undertaken. The majority of these studies document individual landslides, characterising the type of movement and the distribution/abundance in different geographical and physiographical regions. However, there is comparatively limited information concerning the risk of landslides to human beings as indicated by fatality data (Guzzetti, 2000).

Probably the best national landslide database is that of Italy, where events have been recorded since 1907 (Almagià, 1907, 1910). More recently in 1989, in response to the International Decade of Natural Disaster Reduction, the AVI (Aree Vulnerate Italiane) Project was established to compile an inventory of areas historically affected by landslide and flood events throughout the country, with a view to undertaking a national risk assessment (Guzzetti *et al*, 1994). The completed database provides an inventory of landslides from 1900 to the present day (Guzzetti and Tonelli, 2004) which has subsequently been integrated with other data stored within digital catalogues and databases (for example, fatality data) to create a system called SICI (Sistema Informativo sulle

Catastrofi Idrogeologiche, an Information System on Hydrological and Geomorphological Catastrophes) that provides integrated historical, geographical and bibliographical information on landslides and floods nationally. The data stored within SICI have been used to investigate the geographical distribution of landslides and to explore the patterns and reoccurrence of damaging events. In 1999 a further database of landslides in Italy was compiled listing events that have caused fatalities, injuries, missing people and homelessness (Guzzetti, 2000). The availability of such comprehensive fatality data has enabled the detailed analysis of the spatial patterns and controls governing the occurrence of fatal landslide events on a national scale within Italy.

With the exception of Italy, while a number of individual inventories and databases have been established on national and regional scales, they are often based on varying criteria, with different formats and developed for different purposes. These databases are individually useful, but are often limited in scope and incompatible with other catalogues. In addition, inconsistencies, data gaps and ambiguous terminology make comparisons and the use of the datasets difficult (CRED, 2005).

2.2.2 Evaluating existing global disaster databases

A number of international databases recording the occurrence of natural hazard events currently exist. For example, since 1988 the World Health Organisation collaborating Centre for Research on the Epidemiology of Disasters (CRED) has been maintaining a database of emergency events, termed EM-DAT. This well established database contains information on the occurrence and effects of >12,800 natural and technological disasters (including mass movement events) from 1900 to the present day. The database uses information from various sources including UN agencies, non-governmental organisations, insurance companies, research institutes and media agencies (CRED, 2005). EM-DAT was created in response to the demand for better data on disaster occurrence (Sapir and Misson, 1992) and to a certain extent this has been achieved, with the database recording the essential core data on disaster incidence. However, not all fatal landslides are recorded. For an event to be included it must satisfy at least one of the following criteria:

- 10 or more people reported killed
- 100 people reported affected
- Declaration of a state of emergency
- Call for international assistance

By excluding landslides events that have triggered <10 fatalities, EM-DAT underestimates the global impact of mass movement events. Analysing the magnitude-frequency relationship for the number of deaths per landslide event calculated from Alexander's (2005) landslide database suggests that ~27% of events recorded resulted in between one and ten fatalities. Based upon EM-DAT's criteria, these landslides would not be included in the database.

Other established global hazard databases include Munich Re's Natural Hazards Assessment Network (NATHAN), which provides detailed information on the date, location, event magnitude and the hazard impacts (including the number of fatalities) of a number of natural disasters (ESRI, 2005). In addition, The Earth Institute at Columbia University and the World Bank's Hazard Management Unit, have undertaken a project to identify countries or regions where people or economic activities are at extreme risk from multiple natural hazards (Mastriani and Tobin, 2004). Risk of mortality and economic loss from six hazards, including landslide events, has been calculated and the global distribution of highest-risk disaster hotspots mapped (figure 2.1). These maps can be used to identify regions and countries that are particularly vulnerable to disasters, increasing understanding of the global spatial distribution of events and disaster related fatalities.

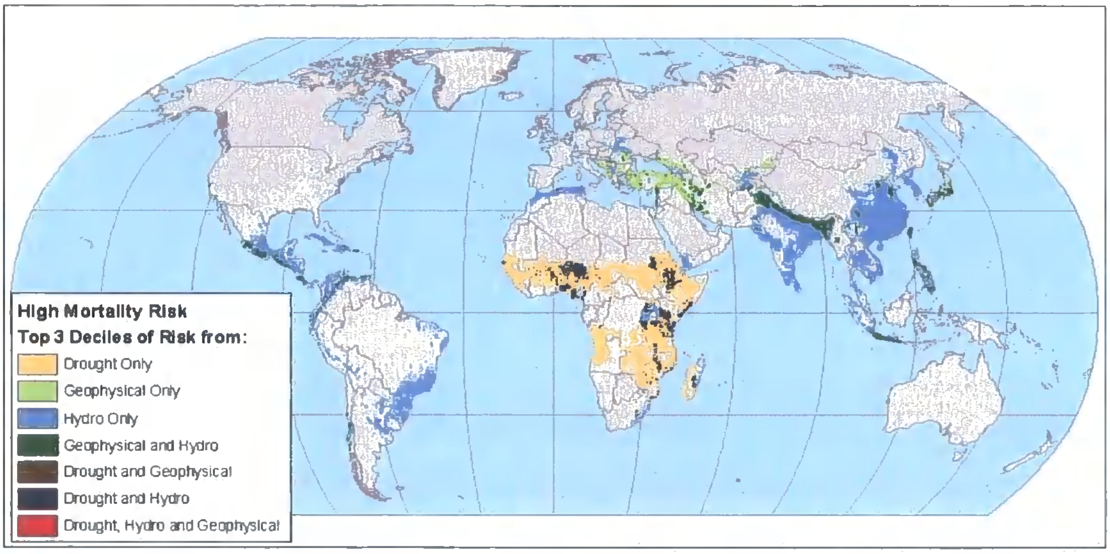


Figure 2.1 Mortality risks from natural disasters (Earth Institute, Columbia University, 2004).

2.2.3 Using fatality data as an indicator of landslide occurrence

For the purposes of this study human fatalities are used as the measure of landslide occurrence. While there are undoubtedly flaws in using this data as an indicator of landslide activity, research suggests that fatality data is reasonably reliably recorded, even in remote areas and less developed countries, providing a relatively reliable and spatially consistent dataset for analysis (Petley *et al*, 2005). In addition, when attempting to analyse relatively frequent events, characterised by relatively low numbers of fatalities, these are the most suitable data. Alternative measures of landslide hazard such as economic impact would undoubtedly result in a more spatially-inconsistent dataset (Petley *et al*, 2005).

Kelman (2005) has undertaken extensive research into disaster deaths and the use of fatality data as an indicator of the impact of hazards on society. The main problem with using fatality data is that the number of persons reported killed by a landslide may change over time (see Kelman, 2005 and Combs *et al*, 1999). Initial fatality estimates attempt to include the total number of disaster attributed deaths, including the number of people confirmed dead in the immediate post impact period and the subsequent loss of the seriously injured. Updated fatality estimates (if they are revised), may include those who have been missing for an extensive period and are subsequently presumed to be dead (Sapir and Misson, 1992). This was an area for consideration when designing the project methodology.

2.2.4 Data sources

The main sources of landslide fatality data are existing catalogues and archives, news reports, interviews, technical/scientific documents, NGO and UN agency situation reports and field reports compiled by disaster workers. The quality and reliability of reported data varies significantly between sources, along with the type of information documented (table 2.1).

News reports from one of the main sources of information in databases. However, while global coverage may be reasonably good, news reports introduce a cultural and professional bias in the reporting of numbers and disaster details (Shah, 1983; Guzzetti *et al*, 1994). In addition, while 'big disasters' are considered newsworthy, smaller events are often comparatively underreported. The news media tends to focus on large magnitude events, particularly those affecting urban areas or well-known structures. Comparatively, rural disaster losses are less concentrated and less dramatic and as a result go unreported (Lewis, 1984). As a result, the full extent of the impact of hazards in rural areas has been largely unrecognised.

Table 2.1 An evaluation of the information sources used to compile the AVI Project (adapted from Guzzetti *et al*, 1994: 626-627).

Newspapers	**Technical and scientific documents**	**Interviews with field experts**
• Emphasis on large magnitude events affecting urban areas. • Events of low magnitude were generally under-reported. The full extent of damage within rural areas is comparatively unknown. • Emphasis placed on the re-activation / repetition of landslide events. • Date and triggering mechanisms tended to be reliably reported. • Geotechnical data e.g. the type of movement was seldom reported.	• Provided detailed, high quality information including the geological, morphological and geotechnical characteristics of a small number of events. • Include detailed location and geometrical characteristics of the land-slide. • Social and economic impacts rarely covered.	• Provided a comprehensive overview of areas historically affected by landslides.

Spatial bias is also a substantial problem. For example, Shah (1983) noted that for landslide data there was far more comprehensive coverage for the USA, while Africa, Europe, China and the USSR were comparatively underrepresented or unrepresented. These findings were attributed to poor communication networks and a lack of infrastructure required to undertake the comprehensive reporting of disasters.

In comparison, technical and scientific documents provide detailed, high quality data, but coverage is generally limited to a small number of events and the social and economic impacts are rarely discussed (Guzzetti *et al*, 1994). Calcaterra and Parise (2001), in analysing the contribution of historical information in the assessment of landslide hazards, noted that public archives, consulting companies, geologists, and homeowners can be useful sources of information, particularly regarding the location of the landslide events and the resulting damage. However, these sources proved to be less useful in determining dates of occurrence, which often proved difficult to verify.

A number of additional problems can be encountered when analysing landslide fatality data (Guzzetti, 2000):

- **Preparing the catalogue** – The date of occurrence is often unknown, incomplete or uncertain, or, it can vary between sources.
- **Fatality/casualty data** – The number of fatalities and casualties are often poorly reported and in some cases only a qualitative description is given (i.e. few, many, several hundred). Some archives may provide little or no information on the human impact of the landslide events, and large discrepancies in reported numbers are common. It is widely acknowledged that disaster reporting sources often have a vested interest in the numbers they report and figures may therefore be inflated or deflated according to the socio-political situation (Sapir and Mission, 1992).

- **Recognising an event as a landslide** – There is often uncertainty as to the definition of a landslide. Debris flows or torrents are often reported as floods rather than mass movements. If a meteorological event causes both flooding and landsliding, often only the flooding is reported or the impact of the hazard, for example the number of fatalities, is attributed to the flooding alone. As landslides are often secondary hazards, it is difficult to separate the direct impacts of mass movement from the impacts associated with floods, earthquakes and other triggering agents (Alexander, 2005).
- **Multiple landslide events** – Where a number of landslides have been triggered by a single precursor (for example, seismic shaking) the number of slope failures may be unknown and if fatalities/casualties are reported, only a total number may be recorded.
- **Representivity** – Inventories tend to be compiled over a limited and selected period of time. This raises issues of representivity when attempting to explain longer term trends in landslide occurrence, particularly as the impacts of natural disasters are seen to vary temporally.
- **Importance of cross-checking** – Data should be cross checked and verified with other data sources including referenced journals and other established databases to minimise errors associated with data collection (Calcaterra and Parise, 2001).

A final problem to note is the use of criteria to determine whether an event qualifies for entry into the database (Shah, 1983). For example, only including landslides that have caused 100 or more fatalities or at least 100 injuries (the inventory criteria of Sheehan and Hewitt, 1969) is a particularly crude form of assessment. A landslide disaster with 99 fatalities would be excluded from a database of major landslide hazards, while a mass movement event injuring 100 people would be cited.

2.2.5 Summary

Over the last decade there has been considerable improvement in the quality and availability of disaster data, reflecting the development of global telecommunications and the information technology revolution (Alexander, 1997). However, a number of problems have been identified with the collection and assimilation of data on the occurrence and distribution of landslide hazard events. These include the vagueness and imprecision of information (for example, location) and uncertain or incorrect dates of occurrence (Calcaterra and Parise, 2001). In addition, information on hazard impacts, for example landslide fatalities, can be sketchy and often exaggerated (Alexander, 1993). For example, the media are often seen to accept and repeat wild estimates (Tobin and Montz, 1997) highlighting the need to treat media sourced fatality data with caution. In general not all significant landslide events are reported by the news media and aid agencies. Significant under-reporting of disaster impacts, including the damage and the number of casualties, has been noted and information on landslide hazards is published far less thoroughly and systematically than other hazard events, for example earthquakes and tropical cyclones (Alexander, 2005). Data validation is therefore necessary prior to undertaking any form of data analysis.

2.3 ANALYSING THE SPATIAL PATTERNS AND CONTROLS OF DISASTER OCCURRENCE

2.3.1 Introduction

The literature review thus far has focused on the collection of hazard data and fatality statistics. A number of papers have been written that use such datasets to examine the broad global trends in the occurrence of natural disasters, including landslide events. These include the early work of Sheehan and Hewitt (1969) who undertook a pilot survey attempting to compile an inventory of the type, recurrence, location and impact of all forms of natural hazard. More recent studies include an analysis of landslide vulnerability by Alexander (2005) based upon ~350 'significant' landslide events that occurred between 1993 and 2002. This sub-chapter will outline, discuss and critique these studies, with a view to determining the depth of current understanding regarding the spatial patterns and controls of landslide occurrence.

2.3.2 Early disaster studies

Dworkin (1974) and Shah (1983) updated the early work of Sheehan and Hewitt (1969) cited above. News wire reports and encyclopaedia year books were used to compile a dataset of global hazard events including earthquakes, volcanic eruptions, landslides and flood events. The following observations were made:

- the number of natural disasters was increasing over time.
- high death tolls were a characteristic of less developed, low income countries.

More than twenty years on, these are still the common held perceptions regarding the spatial and temporal occurrence of natural disasters (Alcántara-Ayala, 2002).

2.3.3 Landslide studies

Alexander (1989, 2005) has undertaken research focusing specifically on the occurrence and distribution of global landslide hazards which has included the analysis of the fatality and casualty patterns and the economic impacts of global mass movement events. Alexander (1989) examined 45 sudden-impact urban landslide disasters occurring between 1584 and 1988. These events resulted in a total of 286,000 fatalities. While the author acknowledged that this was by no means a complete inventory of events over the time period, it illustrated the heterogeneity of death tolls resulting from mass movement events. Fatalities were seen to range from 1 in Surte, Sweden to 200,000 deaths from a landslide in China.

In addition to being incomplete, many of the landslide disasters recorded were composite events, for example, earthquake triggered landslides. No attempt was made to determine the number of fatalities that resulted directly from the landslide events alone. In addition, Alexander's study highlighted the vulnerability of the urban environment with limited to no consideration being given to the impact of landslides in rural areas. This has perhaps produced a spatially biased and skewed picture of fatal landslide occurrence.

Following his earlier study, Alexander (2005) undertook an in-depth analysis of global mass movement events between August 1993 and May 2002. A dataset of landslide disasters was compiled based on news reports and NGO/UN agency situation reports, with the aim of providing a comprehensive picture of global landslide impact. The study included a regional breakdown of the occurrence of landslide disasters, an analysis of the number of fatalities and triggering mechanisms of the events. While again the author identified a number of limitations with the compiled dataset (these were largely concerned with sourcing reliable data – see section 2.2), this is without doubt the most comprehensive global analysis available to date.

Alexander's analysis concentrated on human vulnerability patterns, including the spatial distribution of vulnerability analysed by cause. Consideration was given to issues of poverty and inequality, that is the 'human' dimension of disaster studies and the following conclusions were made:

- Countries subject to hurricane-force storms or torrential monsoon rains and countries with seismically active orogens are the most susceptible to landslide disasters.
- Latin America furnished the highest deaths tolls from landslide events followed by Central and East Asia.
- Landslide-induced mortality was highest in the poorest countries of the world.
- Deaths per landslide event were generally low (50% of the dataset was characterised by ≤ 10 fatalities per fatal landslide event).
- The predominant trigger of landslide activity was high intensity and prolonged rainfall often associated with tropical cyclones.
- Earthquakes and volcanic activity were a far less frequent trigger of landslide activity.
- Shanty-style settlements were seen to be particularly vulnerable to landslide events.

2.3.4 Summary

Building upon more general natural disaster studies, Alexander (2005) has outlined the broad spatial trends in global landslide activity generating a more comprehensive picture of landslide impacts which has been used to analyse human vulnerability patterns. An analysis of the temporal trends in landslide occurrence including annual and interannual variations would undoubtedly strengthen this study and lead to a more detailed understanding of the causative factors and triggering mechanisms of landslide activity.

2.4 PHYSICAL CAUSES AND TRIGGERING MECHANISMS OF FATAL LANDSLIDE EVENTS

2.4.1 Introduction

The term landslide refers to the movement of slope-forming material including rock, debris or soil under gravity (Glade and Crozier, 2005; Crozier, 1999; Cruden and Varnes, 1996). The actual type of movement (including falls, slides and flows) is determined by a number of factors that include the geology, material strength, slope configuration and pore water pressure (Dikau *et al*, 1996). Landslides can have several causes (table 2.2) and these may be geological, morphological, physical or human in nature (Alexander, 1992; Cruden and Varnes, 1996), but only one trigger (Varnes, 1978).

Table 2.2 Landslide causes (USGS, 2004).

Geological Causes	**Morphological Causes**	**Human Causes**
• Weak or sensitive materials • Weathered materials • Sheared, jointed, or fissured materials • Adversely orientated discontinuity e.g. bedding planes and faults • Contrast in permeability and/or stiffness in materials	• Tectonic or volcanic uplift • Glacial rebound • Fluvial, wave, or glacial erosion of toe slope or lateral margins • Subterranean erosion • Deposition loading slope or its crest • Vegetation removal (by fire or drought) • Thawing • Freeze-thaw weathering • Shrink-swell weathering	• Excavation of slope or its toe • Loading of slope or its crest • Deforestation • Irrigation • Mining • Artificial vibration • Water leakage from utilities

The term trigger refers to an external stimulus for example, intense rainfall, rapid snow melt, seismic shaking, volcanic eruption, coastal erosion or the failure of natural dams that cause an immediate or near-immediate response in the form of landslide activity (Schuster and Wieczorek, 2002). The landslide trigger may activate the landslide by rapidly increasing the shear stresses or pore pressures by ground acceleration due to seismic activity, by removing lateral support, by reducing the strength of slope materials or by initiating debris flow activity (Schuster and Wieczorek, 2002).

Mass movements may occur instantaneously following a specific trigger or may occur following a delayed response to the critical triggering conditions, for example landsliding may occur after a prolonged rainfall event which gradually increases the pore-water pressure (Glade and Crozier, 2005). This highlights the importance of pre-existing or antecedent conditions which may initiate slope instability (Gerrard and Gardner, 2000; Schuster and Wieczorek, 2002). Landslides may move quickly down slope at several metres per second or may creep at very slow rates of only a few millimetres per year (Glade and Crozier, 2005). Fast-moving landslides including rockfalls, rockslides and rock avalanches often cause the highest number of landslide-induced fatalities (Guzzetti, 2000; Alexander, 2005).

Glade and Crozier (2005) identified the following conditions promoting mass movement:

- **Predisposing factors** (factors influencing stability) e.g. geology.
- **Preparatory factors** (factors reducing slope stability) e.g. weathering or tectonic uplift. Montgomery *et al* (2001) and Finlayson and Montgomery (2002) highlight the importance of relief and average precipitation in influencing erosion rates.

- **Triggering factors** (factors initiating movement) e.g. high intensity precipitation.
- **Sustaining factors** (factors influencing the duration, rate and form of movement).

These factors determine the magnitude, velocity and frequency of occurrence of fatal mass movement events.

The most common natural landslide triggers include high intensity precipitation, rapid snowmelt, water-level change, volcanic activity and seismic shaking (Wieczorek, 1996). Alexander (2005) analysed the occurrence and distribution of global landslide disasters between 1993 and 2002 and suggested that episodes of high landslide damage were mainly caused by intense and prolonged precipitation associated with tropical storms and flooding, while earthquakes and volcanic activity were seen to be far less frequent but still significant triggers. In an attempt to understand the global spatial distribution of fatal landslides, these trigger mechanisms will be discussed.

2.4.2 Rainfall-induced landslides

Many studies have been undertaken examining the relationship between rainfall and landslide activity (Wieczorek, 1996; Rosenfeld, 1998; Gerrard and Gardner, 2000; Glade, 2000; Dai *et al*, 2003; Gabet *et al*, 2004). The relationship between rainfall and mass movement is associated with infiltration and increases in pore water pressures that reduce shear resistance on a slope and encourage downward movement of material (Tsaparas *et al*, 2002). Storms that produce intense rainfall for relatively short periods (several hours) and events of a more moderate intensity (lasting several days) have been observed to trigger abundant landslides in a number of regions (Wieczorek, 1996).

Fatal landslide events are often associated with large-scale weather systems. These include:

- **Tropical cyclones, hurricanes and typhoon events** (Alcántara-Ayala, 2004). Examples include the mudflows in Haiti in 2004 triggered by heavy rains from Hurricane Jeanne resulting in ~3006 fatalities and the volcanic flank collapse of Casita Volcano, Nicaragua following torrential rains associated with Hurricane Mitch in 1998 (author's dataset).
- **The annual monsoon** (Gerrard and Gardner, 2000a).

  Both North America and Asia are affected by monsoon systems which are associated with high seasonal rainfall. Examples include the catastrophic mass movements triggered by monsoon rains at Malpa in the Kali Valley, Kumaun Himalaya, India which killed 221 people (Paul *et al*, 2000). In addition, research undertaken by Petley *et al* (2005) into the temporal occurrence of fatal landslide events suggested that the majority of fatal landslides in 2003 were triggered by rainfall associated with the South Asian monsoon system.
- **Tropical perturbations** (Alcántara-Ayala, 2004).

  Tropical perturbations (a form of atmospheric disturbance) have been associated with exceptionally high rainfall totals and extensive landsliding in South America. For example, the highest rainfall totals recorded in Mexico were associated with tropical perturbations and depressions that triggered hundreds of landslides in the province of Puebla in October 1999 (Alcántara-Ayala, 2004). In addition, a detailed rainfall analysis undertaken in Nepal suggested that other weather systems, for example atmospheric disturbances, are as effective as monsoons in providing rainfall and have subsequently triggered a number of mass movement events (Shrestha, 2000).

2.4.3 El Nino events, precipitation patterns and rainfall-induced landslides

It is frequently stated that landslide occurrence is controlled in part by the occurrence of El Nino Southern Oscillation (ENSO) events. For example, in the Americas, El Nino events are identified as a major trigger of large scale regional landslide activity (Schuster and Highland, 2001; Reynolds *et al*, 2003). Ngecu and Mathu (1999) also document and discuss some of the fatal landslides triggered by the extraordinarily heavy rainfall in Kenya between May 1997 and February 1998. This period of intense precipitation occurred during the dry season and was attributed to the El Nino effect. During this time widespread landsliding and flooding was experienced resulting in several hundreds of fatalities and injuries. Petley *et al* (2005) analysed the relationship between annual landslide fatality totals and the occurrence of El Nino events. However, their findings seemed inconsistent with the wider literature with their dataset providing no evidence to suggest that El Nino events play a substantial role in the occurrence of global landslide fatalities.

Links or 'teleconnections' have been made between the occurrence of El Nino events and anomalies in monsoon rainfall (Verma, 1994; Kane, 1998; Khole, 2000; Gadgil *et al*, 2004). For example, during El Niño years, the intensity of the Indian summer monsoon rainfall is reduced (Pai, 2004). With monsoonal rainfall being a dominant trigger of landslide activity it would be of interest to investigate the connections between El Nino events, monsoon rainfall anomalies and landslide occurrence.

2.4.4 Global climate change and landslide occurrence

Extensive research has been undertaken to determine the potential impacts of global warming on natural hazard occurrence (Alexander 1995; UNDP, 2004; Berz, 2005; Webster *et al*, 2005). For example, findings of a study undertaken in the early 1990s suggested that increasing global and regional temperatures associated with global warming may trigger more volatile weather conditions and meteorological extremes (Mitchell and Ericksen, 1992). Warmer ocean waters in the tropics could result in a longer and more intense hurricane season (Tobin and Montoz, 1997; Webster, 2005; Emanuel, 2005). In a recent paper in Nature, Emanuel (2005) published research findings which suggest that tropical cyclones have become increasingly destructive over the past thirty years. These findings were affirmed by Webster *et al* (2005) who observed an increase in tropical cyclone intensity over a similar time period. This is of particular concern as the majority of significant landslide events recorded by Alexander (2005) between 1993 and 2003 were triggered by high intensity or prolonged precipitation often associated with tropical cyclones. An increase in global temperatures and subsequent hurricane activity will undoubtedly affect the frequency of mass movement events and the number of associated landslide fatalities. The temporal variability of landslide occurrence and fatality totals is certainly an area requiring further research.

2.4.5 Earthquake-triggered landslides

Earthquakes have long been recognised as a major trigger of landslide activity (Seed, 1968; Keefer, 1984). Such events are seen to occur in a number of different topographical and geological settings (Wieczorek, 1996) and often cause the majority of casualties associated with earthquake events (Havenith *et al*, 2003). For example, the 2001 El Salvador

Earthquake (magnitude 7.6) triggered the Las Colinas landslide in Balsamo Ridge which caused the greatest loss of life in a single location from an earthquake (Luo *et al*, 2004) with ~585 fatalities (Evans and Bent, 2004).

The majority of seismically induced slope failures are small in size but some result in the displacement of large volumes of material, posing a serious threat to human life and property (Harp and Jibson, 1995). The occurrence of earthquake induced landslides is based on two parameters:

- the susceptibility of the slopes to instability;
- the intensity of the earthquake shaking

(Bommer and Rodríguez, 2002).

According to Khazai and Sitar (2003) in a recent study evaluating the factors controlling earthquake-induced landslides caused by the 1999 magnitude 7.3 Chi-Chi earthquake in Taiwan, ground motion was found to be the most significant factor in triggering the dominant shallow landslides. Only very large catastrophic dip slope failures could be attributed to geological setting (Khazai and Sitar, 2003). When comparisons were made between the Chi-Chi earthquake and the Northridge and Loma Prieta events, significant similarities in the frequency and distribution of the different landslide types were observed. These findings are endorsed by Havenith *et al* (2003) who, having analysed the influence of topographical and other site specific amplification effects on the initiation of earthquake induced landslides, suspect that ground motion dynamics contribute significantly to slope failure.

Keefer (1984) undertook a detailed study of earthquake triggered landslides, analysing data from 40 historic earthquake events to determine their characteristics and the impact of climate, geology and seismic setting. This study was updated by Rodriguez *et al* (1999) and yielded similar results. Fourteen types of landslide were identified, the most abundant including rockfalls, disrupted soil slides and rock slide events. Rapid soil flows and rock avalanches (under certain geological conditions) were seen to cause the greatest number of fatalities. This was largely due to the burial of cities or villages located on gently sloping ground several kilometres from the sites of landslide initiation. Rock falls, the most abundant seismically triggered landslide events, were seen to occur in virtually all rock types on slopes steeper than 40°. While the areas of risk were limited by the trajectories and movements of material, seismically-triggered rock falls were still the third leading cause of death (Rodriguez *et al*, 1999). Other fatal earthquake-induced landslides include soil slumps, block slides, soil lateral spreads, sub-aqueous landslides and rock slumps. However, these events only occur under certain circumstances, reducing their threat to human life.

Examples of earthquake induced slope failures include the 1970, Richter magnitude 7.7 earthquake in Peru which triggered earthquake triggered a debris avalanche from the north peak of the Huascaran, Cordillera Blanca burying the town of Yungay and part of Ranrahirca, resulting in >18,000 fatalities (Plafker *et al*, 1971). More recently, the 1999 Chi-Chi earthquake triggered >20,000 landslides totalling 113 km^3 throughout central Taiwan (Lin *et al*, 2003; Hung *et al*, 2000; Wang *et al*, 2000). The general characteristics of the landslides were similar to those observed in other mountainous regions following large earthquake events and included relatively shallow slides on very steep slopes, rock falls, deep seated failures and large coherent deep-seated landslides (Khazai and Sitar, 2003).

2.4.6 Volcano related ground failures

Volcanic eruptions have triggered some of the largest and most catastrophic mass movement events recorded (Wieczorek, 1996). These include lahars (volcanic mudflows), landslides and debris avalanches. Scott *et al* (2001) have undertaken research into catastrophic debris flows in volcanic terrains. Communities occupying low-lying areas adjacent to volcanoes are vulnerable to significant volcanic flows in addition to the hazards associated directly with eruptions. The greatest risk is from debris flows which have the potential to travel over 100 kilometres (Scott, *et al*, 2001).

Lahars or volcanic mudflows occur widely on steep volcanic flanks enlarging by bulking as they flow (Scott *et al*, 2005). Examples include the debris flows associated with the 1985 eruption of the Nevado del Ruiz volcano in Colombia (Lowe *et al*, 1986; Naranjo *et al*, 1986; Pierson *et al*, 1990; Sigurdsson and Carey, 1986; Thouret, 1990; Thouret *et al*, 1990). Heat from the pyroclastic flows and surges associated with this relatively small eruption melted glacial ice near the summit of the volcano and generated meltwater floods that developed into lahars as soil and loose sediments became incorporated. The largest flow was >45 m deep and moved at c.12 ms^{-1}, killing 25,000 people in Armero at the base of the volcano (Lowe *et al*, 1986).

Landslides are frequently the result of volcanic instability. Active volcanoes dynamically evolve, growing internally by magma intrusion and externally by the accumulation of layers of lava and pyroclastic deposits on the flanks of the volcano (McGuire, 1994). This can result in destabilisation by overloading, oversteepening and mass removal. This, coupled with seismic shaking and high intensity precipitation, has been seen to trigger edifice failure (sector collapse) and landsliding which have been described as one of the most hazardous geological processes due to their volume and velocity (Hürlimann *et al*, 2000).

Volcanic landslides frequently transform into debris avalanches and debris flows (Kerle and Van Wyk de Vries, 2001). For example, during Hurricane Mitch in 1998, heavy rainfall triggered a rockslide-debris avalanche on the southern flank of the Casita volcano, Nicaragua. The avalanche evolved into a debris flood and, with an increasing concentration of entrained sediment, a lahar which killed approximately 2500 people in the towns of El Porvenir, Rolando Rodrigues and other small hamlets in the lowland area to the south of the volcano (Scott *et al*, 2005).

An additional hazard associated with volcanic-landslides are tsunamis (McGuire, 2000). The impact of the lateral collapse of an oceanic island volcano for example, the Cumbre Vieja Volcano on the island of La Palma, in the Canary Islands has the potential to generate destructive tsunami waves (Ward and Day, 2001). Research suggests that waves generated by the run out of a 500 km^3 landslide into the ocean at 100 m/s could transit the entire Atlantic Basin threatening the American coast with tsunami waves 10-25 m in height (Ward and Day, 2001). Such an event would result in the largest impact of a landslide imaginable.

2.4.7 Landslide dam-break floods

Landslide dams can be defined as temporary or permanent stream blockages resulting from mass movements (Korup, 2002). Such movements include rock and debris avalanches, rock and soil slumps and slides, and mud debris and earth flows (Costa and Schuster, 1988). The most common landslide triggering mechanisms include excessive rainfall, snowmelt and seismic activity, although others have also been documented, and include volcanic and anthropogenic activity (Korup, 2002). Many landslide dams fail shortly after formation. This may occur naturally by overtopping or through artificial breaching.

A number of landslide dams have failed catastrophically, resulting in flooding and loss of life (Costa and Schuster, 1988 and Walder and O'Connor, 1997). Examples include the failure of the Deixi landslide dam on the Min River in central China in 1933 which resulted in the death of at least 2,423 people (Costa and Schuster, 1988). Such events occur infrequently, but the available warning times may be very short (Davies, *pers comm.*).

2.4.8 Summary

This sub-chapter has outlined the main physical causative factors and triggering mechanisms of fatal landslide activity based upon the findings of Alexander (2005), including high intensity and prolonged rainfall, earthquakes and volcanic activity. Consideration has also been given to the predisposing and preparatory factors including slope angle, geology and tectonic stability, the overriding factors governing the spatial distribution of landslide events. Issues of climate change and temporal variability have also been introduced and identified as areas requiring further research.

2.5 HUMAN CAUSES OF FATAL LANDSLIDE DISASTERS

'Society, rather than nature, decides who is more likely to be exposed to dangerous geophysical agents' (Hewitt, 1997: 141).

2.5.1 Introduction

During the 1970s social scientists began to challenge the accepted notion that the observed increase in the occurrence of natural disasters was attributable solely to increases in physical phenomena (Bankoff, 2001). Instead, Hewitt and Barton (1971) saw disasters as a function of both the physical event and the state of human society. This human-environment relationship was developed further by Westgate and O'Keefe (1976) and Susman *et al* (1983), the latter as part of Hewitt's radical critique. Hewitt and Barton (1971) explored the notion of vulnerability, a term that has become increasingly fashionable, with many influential writers viewing this discourse as the key to understanding disasters (Wisner *et al*, 2004 and Alexander, 2005). As a result, since the publication of Hewitt and Barton's (1971) benchmark paper, there has been an increasing tendency to view disasters as the consequence of social conditions, rather than the geophysical agents that precipitate them (Quarantelli, 1995). This sub-chapter will explore the human dimension of landslide disasters, with a view to identifying a series of human causative factors and triggering mechanisms of landslide activity.

2.5.2 Vulnerability to landslide hazards – The alternative discourse

It should be noted that there is no single accepted definition of vulnerability (Cutter, 1996; Weichselgartner, 2001; Alexander, 2005). For the purpose of this study therefore the broad working definition proposed by Alexander (2005) will be used: vulnerability is the

'potential for losses or other adverse impacts' (pp.176). Vulnerability is based upon *'the characteristics of a person or group and their situation that influence their capacity to anticipate, cope with, resist and recover from the impact of natural disasters'* (Wisner *et al*, 2004:11). Vulnerability can be seen to vary both spatially and temporally along with the natural environment and society (Uitto, 1998; Cutter *et al*, 2003; Hufschmidt *et al*, 2005a).

Cutter *et al* (2003) identified three main themes in vulnerability research:

- the identification of **conditions that make people or places vulnerable** to extreme natural events (Burton *et al*, 1993; Anderson, 2000);
- the assumption that vulnerability is a social condition, a measure of **societal resilience** to hazards (Hewitt, 1997; Wisner *et al*, 2004);
- the integration of **potential exposures** and **societal resilience** with a specific focus on particular places or regions (Kasperson *et al*, 1995; Cutter *et al*, 2000).

Proponents of vulnerability as a conceptual explanation therefore believe that while hazards may be natural, disasters are not (Bankoff, 2001). Smith (2004) makes a clear distinction between the two:

- The term hazard refers to all naturally occurring processes or events with the potential to create loss.
- A disaster describes a hazard event where large numbers of people are killed, injured or affected in some way.

This definition is endorsed by Degg (1992) who notes that disaster can only be used to describe an event when the losses exceed the accepted norms within a given society. Disasters are therefore viewed as a product of the social, political and economic environments that structure the lives of different groups of people (Wisner *et al*, 2004). Similarly, risk, defined as the probability of a hazard occurring (Smith, 2004), is seen to depend primarily upon on-going societal conditions (Hewitt, 1997). This 'dual character' of natural disasters (Alcántara-Ayala, 2002) is summarised in figure 2.2.

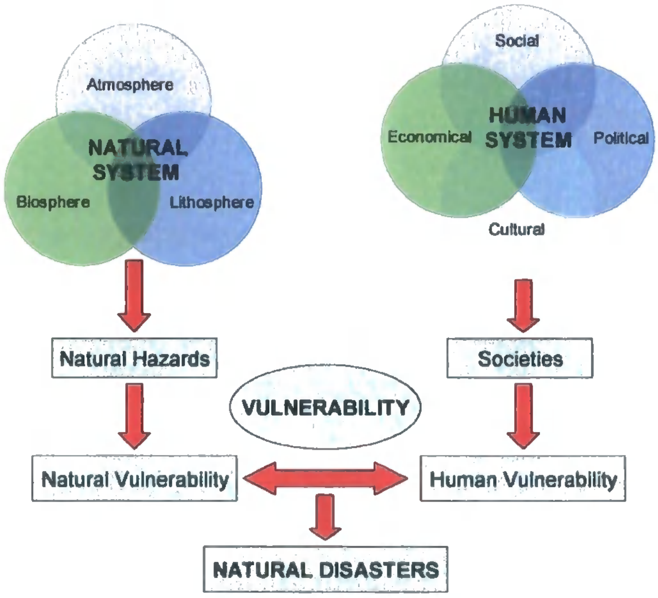


Figure 2.2 A schematic representation of vulnerability and the occurrence of natural disasters (adapted from Alcántara-Ayala, 2002:120).

The model presented in figure 2.2 is based upon two very separate systems which interact when a hazard occurs. However, as observed by Cutter (1996) and Hufschmidt *et al* (2005a) natural hazards are not isolated events but are complex features connected to the social system. It is this connectivity between the physical and social systems that is the main characteristic of natural risk (Hufschmidt *et al*, 2005a). For example, the Karakoram Himalaya is characterised by tectonically destabilised slopes and high climatic inputs and is therefore vulnerable to earthquakes, snow avalanches and landslide hazards (Hewitt, 2004).

However, it is the interaction between society (the inhabitants of the hundreds of villages along the valleys in the Karakoram) and the geophysical environment or the 'geosystem' that determines risk, hazard potential and vulnerability, that can be summarised as a 'hazard of place' model (Cutter, 1996; Cutter *et al*, 2003) (Figure 2.3).

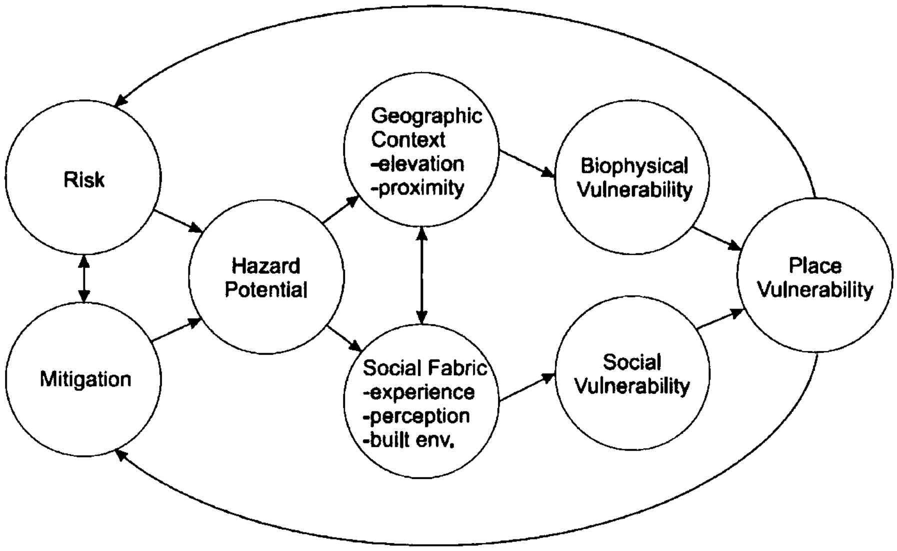


Figure 2.3 The hazards-of-place model of vulnerability (Cutter *et al*, 2003 modified from Cutter, 1996).

Other models based upon the interaction between vulnerability and hazard also exist including the 'pressure and release (PAR) model' proposed by Wisner *et al* (2004). The PAR model provides a 'chain of explanation' of the factors giving rise to vulnerability. These include:

- *root causes* (general economic, demographic and political processes within society, the functioning of the state and the influence of the world economy).

- *dynamic pressures* (the processes and activities that translate the effects of the root causes both spatially and temporally into unsafe conditions e.g. rapid urbanisation).
- *unsafe conditions* (the specific forms in which the vulnerability of a population is expressed in time and space in conjunction with a hazard e.g. people living in hazardous locations in unsafe buildings).

These 'pressures' are discussed below.

2.5.3 Human vulnerability – the causative factors

Underdevelopment

Natural disasters can be viewed as ***"a cause and a product of failed development"*** (UNDP, 2004).

It is often argued that the distribution of natural disasters is strongly correlated with the geography of underdevelopment (Chardon, 1999; Alcántara-Ayala, 2002), whereby the vulnerability of society to natural hazards is socially constructed, rooted in historical, cultural, social and economic processes that reduce the ability of an individual or society to cope with disaster (Weichselgartner, 2001). As a result many researchers are of the opinion that it is difficult to separate natural disasters from the broader issues of development (Jeffery, 1982; Alcántara-Ayala, 2002).

Underdevelopment is a process largely affecting the poorer countries of the world, where societies suffer from changes imposed from outside the community, in the interests of the outsiders (Susman *et al*, 1983). With its colonial roots, underdevelopment can be viewed as a continual processes resulting from a world economy which perpetuates technological dependency and unequal exchange (Susman *et al*, 1983; Alexander, 1997 and Bankoff, 2001). Indeed some early works focusing on the non-naturalness of disasters took a very anti-capitalist stance (O'Keefe *et al*, 1976). Cannon (1994), Pelling (2003) and Wisner *et al* (2004) examined these issues in depth, including the impact of the debt crisis on vulnerability. Third World debt can be viewed as holding development back and as such increases poverty, deprivation, marginalisation and environmental degradation. These factors in turn increase the susceptibility of the environment to hazard and increase the vulnerability of the population to disaster.

The occurrence of environmental disasters may setback development (Pelling, 2003; UNDP, 2004). Examples include the impact of Hurricane Mitch in 1998 in Honduras and Nicaragua, where human losses and damage to physical infrastructure, housing and crops were predicted to have hindered development efforts by a decade or more (Bradshaw *et al*, 2002 cited in Pelling, 2003). This will undoubtedly further increase the vulnerability of the population to the occurrence of subsequent natural hazard events.

In addition to the previous definition introduced, vulnerability is often viewed as a function of the level of economic development of a country (Alexander, 1995). The foundations of this were illustrated in a United Nations Development Programme Report (2004) on disaster risk. The report demonstrated that countries with similar patterns of natural hazards were characterised by widely varying levels of disaster risk attributed to varying development paths and processes. This is illustrated in figure 2.4, whereby A represents countries characterised by a very low level of resources and hence slightly reduced vulnerability; B, the state of maximum vulnerability (countries characterised by the lowest level of development); C represents the state of minimum vulnerability (correlating with increasing expenditure on mitigation) and D corresponds to countries where increased technology creates new sources of vulnerability. The potential for vulnerability reduction through mitigation is represented by line E, while F illustrates the development gap in mitigation. In short, the highest deaths tolls are seen to occur within less economically developed countries, while the economic impacts are often far greater in more economically developed countries.

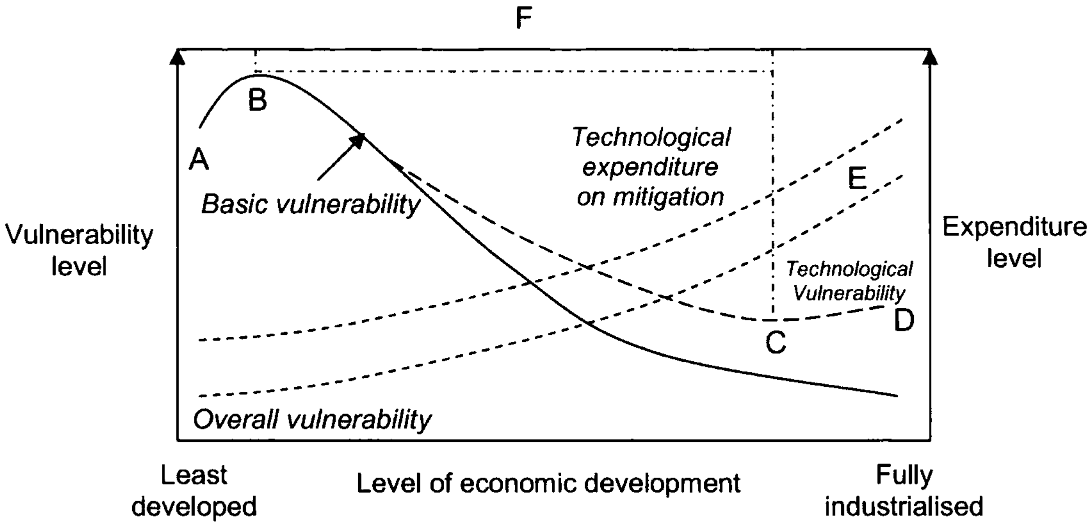
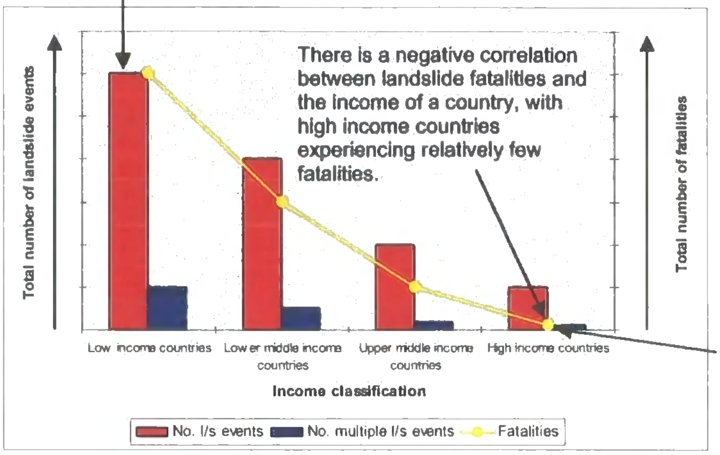


Figure 2.4 Vulnerability to disasters and levels of economic development (Alexander, 1995).

Based upon the above findings the following model has been generated (figure 2.5). Landslide fatalities may be viewed as a function of the level of economic development of a country, with low levels of development being associated with high numbers of fatalities.



The frequency of fatal landslide events is high in low income countries

There is a negative correlation between landslide fatalities and the income of a country, with high income countries experiencing relatively few fatalities.

Low income countries are more vulnerable to landslide disasters due to:

higher population densities and urban growth;

rural-urban migration;

the development of shanty style settlements;

poverty;

exploitation of resources e.g. deforestation.

High income countries have the financial capabilities and expertise to mitigate against landslide disasters reducing the number disasters and disaster related fatalities.

Figure 2.5 The hypothesised landslide fatality model: the occurrence of landslide fatalities is a function of the level of economic development of a country.

Location

Vulnerability is often perceived as being locationally driven, whereby it is a function of the proximity to the source of the hazard/risk (Weichselgartner, 2001). According to Alcántara-Ayala (2002) natural disasters occur worldwide, however their impact is often greater in developing countries. This can be attributed to geographical location and geomorphological setting with developing countries being predominantly located in areas prone to natural hazards.

Many cities were founded in areas known to be highly hazardous locations; for example Lima, Peru is located in an area of high seismicity and has been damaged by a number of high magnitude earthquakes (UNDP, 2004). The settings of many rural communities are also hazardous (UNDP, 2004); for example settled mountain belts where exposed tectonically destabilised slopes are frequently seen to impinge upon routeways and settlements causing injury and fatalities (Alexander, 2005). Examples include the Alps, Himalayas, Karakoram, Hindu Kush and the Andes.

Human livelihoods are often earned in locations that combine opportunities with hazard, thus increasing the exposure of a population and likelihood of disaster (Wisner *et al*, 2004). For example, settlements located near volcanoes were developed to exploit the fertile soils and are highly vulnerable to volcanic hazards (see section 2.4.6). People are also seen to live on rubbish dumps where they may work as informal material recyclers (Westfall, 2001). These garbage heaps are susceptible to failure, an example of the interaction between hazards of natural and technological/man-made origin (UNDP, 2004). For example, in 2000 heavy rains from Typhoon Kai Tak triggered the collapse of a rubbish dump in Payatas on the outskirts of Manila, killing more than 200 people. The dump was home to ~2,000 people who live in shanty-style housing on the garbage heap (Westfall, 2001).

It is important to note that in some cases people choose to live in vulnerable locations (see Hewitt, 1997 chapter 6 for a review of voluntary and involuntary vulnerabilities). Examples include Austrian city dwellers building country homes in the paths of avalanches or Americans locating on Caribbean shores, unaware of the potential of catastrophic tropical storms (Burton *et al*, 1993).

Population growth and urban expansion

"Directly, urban growth is responsible for transforming geomorphological processes into community hazards" (Cooke, 1984).

Based upon figures published by the United Nations Population Information Network (2003) the world population reached 6.3 billion by the beginning of 2003 and is projected to grow to 8.9 billion by 2050. 90% of this growth is predicted to occur within developing countries, many of which are subject to extreme natural events (POPIN, 2003 and The Population Reference Bureau, 2002 cited in Wisner *et al*, 2004). While it can be argued that an increase in population will undoubtedly increase the number of people exposed to natural hazards the simplistic nature of this analysis must be recognised (Wisner *et al*, 2004; UNDP. 2004).

There will also be changes in population distribution with urban population projected to increase from under 50% to 60% by 2030 (United Nations, 1999). This natural demographic increase, coupled with mass migrations, has arguably created areas of highly concentrated vulnerability (Steedman, 1995). According to Wisner *et al* (2004) in the year 2000 there were 19 cities (megacities) with more than 10 million residents. This number is projected to increase to 23 by 2015 with 19 of these cities predicted to be in less developed countries and 8 within moderate to high seismic risk zones (Wisner *et al*, 2004). Indeed half of the urban dwellers in the world's 50 largest cities live within 200 km of active faults known to produce earthquakes of magnitude 7 or greater (Turner *et al*, 1990).

The vulnerability of cities and in particular megacities (cities with populations of >8 million people (Steedman, 1995)) to natural hazards received considerable attention during the International Decade of Natural Disaster reduction (Cross, 2001). Since then much has been written about urban vulnerability (Turner *et al* (1990); Cohen (1990, 1993); Anderson, (1992); Bernstein (1992); Steedman, (1995); Whittow, (1995); Chardon, (1999); Mitchell, (1995, 1998, 1999a, 1999b); Mitchell and Parker, (1995) and Smyth and Royal (2000). In addition, the Munich Reinsurance Company (2005) have developed a 'natural hazard risk index' as part of the 2005 World Conference on Disaster Reduction in an attempt to quantify the risk of disaster from natural hazards within megacities. In short, megacities are frequently identified as 'major arenas' for natural disasters (Mitchell, 1999b).

Urban areas are often perceived as being more vulnerable to disasters due to the number of people concentrated in a defined and limited space (Anderson, 1992; Smyth and Royle, 2000). The physical expansion of cities, often involving the occupation of geomorphically hazard prone lands that were previously avoided and the extensive growth of spontaneous, low-income settlements (often resulting from the lack of regulation and the enforcement of planning laws), has further increased vulnerability (Rosenfeld, 1994; McCall, 1998; Mitchell, 1999b; Sanderson, 2000; Smyth and Royle, 2000; UNDP, 2004). Between 50 and 60% of residents live in informal settlements in Bogota, Bombay, Delhi, Buenos Aires, Lagos and Lusaka; 60 to 70% in Dar es Salaam and Kinshasa and more than 70% in Addis Ababa, Cairo, Casablanca and Luanda (UNDP, 2004). The pressures placed on marginal and unsafe land and its subsequent degradation has resulted in an increase in mudflows, landslides and flash floods (Wisner *et al*, 2004). Examples include the 1999 floods and mudslides in Caracas, Venezuela where 30,000 people were killed and 10,000 people were displaced by the disaster that affected the densely populated hillside suburbs of Caracas (Wisner *et al*, 2004).

Jiménez Días (1992) has undertaken a detailed study to identify the relationship between the squatter (*barrio*) settlements and the incidence and occurrence of slope failure in Caracas, Venezuela. Such events have become an increasing problem as rising populations caused urban growth to take place on surrounding hillsides, with the problem of slope stability being largely ignored. While the *barrios* are illegal settlements, the state does little to stop their spontaneous development (largely through their own political interest). While basic infrastructure and services may be provided, houses are often constructed from waste or non durable materials and little is done to manage the threat of mass movement. The impact of slope modification, the effect of paved areas on runoff generation and the weight of houses on the unstable slopes are some of the factors examined within the paper. Jiménez Días (1992) concluded that the areas increasingly affected by landslides correlate with the zones where rapid development of new settlements has been taking place.

Bull-Kamanga *et al* (2003), Degg (1992) and Alexander (1993) explored the issues of vulnerability in smaller urban centres and rural areas. Research findings suggested that these areas are susceptible to a different set of vulnerabilities stemming from progressive neglect, repression and deprivation of the poor (Alexander, 1993).

Cross (2001) took this one step further and challenged the assumption that megacities and large urban areas are uniquely or excessively vulnerable to natural disasters. Instead, having analysed the major natural disasters that have occurred between 1990 and 2000, Cross (2001) concluded that megacities had no monopoly on disaster losses during this time period, noting that in major metropolitan areas that have experienced disasters, destruction was often greater in outlying communities. Examples include the mudflows triggered by Hurricane Mitch in 1998 which destroyed rural Honduran villages and the town of Posoltega, Nicaragua (IFRCRCS, 1999). In addition, the two most deadliest disasters of the 1990s affected rural villages (Cross, 2001). The 1990 earthquake in Iran initiated landslides killing >50,000 people (Cross, 2001). The impact of the earthquake was far greater in the rural villages, with ~83% of destroyed houses being classified as rural (Fallahi, 1996). A similar situation was experienced in Bangladesh in 1991 where a tropical cyclone caused >13,000 fatalities in mostly rural areas including farming and fishing villages (Cross, 2001).

Cross' findings build on the earlier work of Lewis (1984) who observed that total losses from small and more frequent events are as great as large well publicised disasters. In addition, rural areas often suffer greater proportional and numerical losses than urban areas affected by the same disaster occurrence (Lewis, 1984). Towards the end of the International Decade of Natural Disaster Reduction, the International Federation of Red Cross and Red Crescent Societies (1998) categorically denied that megacities were more 'risky' unless they are associated with poor practice (including environmental policy and disaster mitigation) and weak and ineffective urban governments.

Factors giving rise to a heightened sense of vulnerability in rural areas are outlined below (Cross, 2001):

- Emergency response capabilities are much poorer in rural areas. For example, there may be limited access to emergency medical care. These patterns can be observed in both less developed and more developed countries.
- Communities within rural areas are usually small and relatively isolated making rescue and recovery efforts slow (Hewitt, 1992).
- Hazard mitigation and warming efforts are typically more extensive in major metropolitan areas than in smaller communities and particularly those in rural settings. For example, there may be earthquake proof housing and landslide monitoring (Leimgruber, 1996).
- Engineered works are far more likely to protect large metropolitan areas than smaller communities. For example, insufficient transport infrastructure.
- Disaster response and recovery may be slower in rural areas.

While many rural communities have developed coping strategies that enable them to live and prosper in potentially hazardous environments (for example, shifting cultivation and nomadic cattle herding), vulnerability can rise following environmental degradation and climate change (UNDP, 2004). While urban areas are also susceptible to environmental change, rural areas are believed to be particularly susceptible (UNDP, 2004).

Poverty, society and marginalisation

While poverty is not exactly synonymous with vulnerability, it is very close to being so (Cannon, 1994). As observed within urban areas, the poorest people in rural areas often occupy the most marginal lands (UNDP, 2004). In addition, endemic poverty not only limits choice with respect to location, but also emergency preparedness, and the ability of both government and individuals to respond to natural disasters (Chapman, 1994).

It is often argued that it is society that determines where people live and work and therefore their level of hazard protection and preparedness (Wisner *et al*, 2004). Examining fatal landslides specifically, fewer rich people become victims of landslides as wealth can be used to mitigate against and minimise the impact of hazard events (Wisner *et al*, 2004). However, disaster vulnerability is still present within 'rich' countries. Cannon (1994) uses the example of the USA where low wage earners, unemployed and people discriminated against because of their ethnicity are seen to suffer greater human and material losses from natural disasters. A topical example, although not landslide related, would be the 2005 hurricane related floods in New Orleans.

The degradation of natural resources

Poverty is strongly linked to environmental degradation and there is clear evidence to suggest that this exacerbates the impact of a disaster (Alexander, 1997). Examples include deforestation which has been linked to increasing landslide occurrence (Glade, 2003; Ives, 2004). Land may be cleared for agriculture, road construction or to exploit timber resources, increasing the susceptibility of these felled areas to natural disasters. The extensive upland deforestation that occurred in the Philippines (Bautista, 1990), reduced the stability of volcanic soils, causing debris flows to be far stronger and more destructive (Rodolfo *et al*, 1989). Recent examples include the landslides triggered by typhoon rains in the Philippines in December 2004. These landslides resulted in ~1,000 fatalities (Petley *et al*, 2005) and were heavily linked to illegal logging practices.

While much has been written on population growth putting pressure on land resources, increasing deforestation, overgrazing, cultivation, soil erosion and road construction which have subsequently been linked to landslide and flood events (UNDP, 2004), there is also an alternative view point presented within the literature. Ives (2004) challenges the perceptions held by many institutions, agencies and academics regarding environmental degradation within the Himalaya which he believes lack scientific substantiation and are an exaggeration of the true situation. Empirical analysis and quantification is needed to determine the relationship between environmental degradation and the occurrence of landslide events.

2.5.4 Summary

There has been a clear shift in the conceptualisation of natural disasters from physical or natural events towards the integration of human systems (Alcántara-Ayala, 2002; Weichselgartner, 2001). In this, the traditional direction of causality has been reversed, with vulnerability itself, not physical impact, defined as the root cause of catastrophe (Alexander, 1995). In this sense, physical triggers only transform a *"scenario of pre-configured disaster risk"* (UNDP, 2004: 62).

It could be argued that the rhetoric concerning social vulnerability ignores the geophysical environment which geoscientists would argue is the root cause of natural disasters. Indeed little has been done to associate geomorphology and natural hazards directly (Alcántara-

Ayala, 2002). While vulnerability studies should be viewed as the necessary compliment, rather than the alternative to the hazards perspective, this is rarely the case (Hewitt, 1997). Both the physical and social systems are not being sufficiently represented within current hazard research (Hufschmidt *et al*, 2005a). When analysing the global spatial patterns and controls of fatal landslides it is therefore essential to consider and evaluate the connectivity between these systems.

2.6 RESEARCH HYPOTHESES

Based upon the findings from the literature review undertaken, the following hypotheses have been generated. The landslide database was used to empirically test these statements set out to challenge our current understanding regarding global spatial distribution and temporal occurrence of fatal landslide events.

1. The frequency of fatal landslide events is increasing with time.
2. The occurrence of landslide fatalities is a function of the level of development of a country, with lower levels of development being associated with higher numbers of fatalities.
3. The occurrence and impact of fatal landslides is greater in urban than in rural areas.
4. Areas that have been subject to severe land degradation are more prone to the occurrence of fatal landslide events.
5. Fatal landslides are concentrated in areas characterised by high relative relief, high precipitation inputs and/or areas subject to seismic shaking.
6. Human/social factors are more significant than physical parameters in determining the occurrence of fatal landslides.

3 RESEARCH METHODOLOGY

3.1 Introduction

The methodology adopted is based upon the work of Guzzetti (2000) and Alexander (2005). The research has been undertaken in a series of stages in order to fulfil the research objectives set out in chapter 1.

3.2 Creating a workable database

Prior to undertaking this research the landslide database was essentially a global inventory of fatal landslide events from 1900 to the present day. Information held within the archive included the date, location (at the national, regional and local scale where possible), type of mass movement, size of the event, triggering mechanism, number of fatalities, number of injuries and number of people reported missing. Notes on the landslide impact and details of the resulting damage were also recorded along with a source of the information (Petley *et al*, 2005).

The quality of the data varied considerably throughout the database, but for landslides prior to the 1990's the database was particularly vague with regards to many of the above criteria. Between 1900 and 1994, 300 fatal landslide events were recorded, accounting for 31% of the total number of landslide events featured within the database. In addition, it is likely that this historic record includes only a comparatively small proportion of the total number of events that occurred during this period. In light of these problems, the research presented here has focused on the more detailed and comparatively complete subset from 1st January 1994 to 31st December 2004, which includes approximately 700 fatal landslide events. These represent over 70% of the events recorded in the long term landslide database.

A workable database was created from the landslide inventory. The method adopted was two-fold. First, an attempt was made to improve the database by adding fatal landslide events that had not been previously recorded and by improving the records for landslides within the database. Additional information about individual events was obtained from a range of data sources including online news reports, academic papers, government data, aid agency reports and information gained from personal communication. Useful sources included:

- The Centre for Research on the Epidemiology of Disasters (CRED) EM-DAT database
- Reports by the National Red Cross and Red Crescent Societies.
- IRIN News – the United Nations Office for the Coordination of Humanitarian Affairs.
- Relief Web
- BASICS (British Association for Immediate Care) Avalanche Database which includes landslide events.

A number of regional and national sources were also available including:

- The Asian Disaster Reduction Centre – providing national summaries of countries within Asia.
- Landslide Information System –a record of disastrous landslides in India.

Similar problems to those identified by Guzzetti (2000) and Alexander (2005) (see section 2.2.4) were encountered when adding to the database. Information was often incomplete, unknown or uncertain, in particular in relation to exact date of occurrence, location in space, and the correct number of fatalities. Where possible a range of sources were compared for each landslide event to provide the most reliable information concerning the number of fatalities, injuries and missing people. This cross-checking and verification helped to minimise errors associated with data collection (Calcaterra and Parise, 2001). Where more than one value was available for the same event the method used by Guzzetti (2000) was adopted in which the figure judged to be the best documented or reliable was chosen. Thus, for example, the figures reported in an academic journal or a UN report would be selected over a news report. When no such criteria could be applied, the modal value was used to avoid over and underestimations of the fatality total.

An attempt was also made to verify existing entries within the database. In many cases online news reports that were the original source of information for landslide events were no longer available which was a particular problem for events occurring before 1998. Where possible, alternative sources were investigated and the information was cross-checked.

Reference was also made to meteorological reports, including the National Climatic Data Centre Annual Climate Report (NOAA/NCDC, 2003, 2004, 2005), which provide information on annual monsoon strength and on the occurrence of global meteorological hazards, including tropical cyclone events. The United States Geological Survey Earthquake Hazard Programme database was also used to provide information on historical and current earthquake activity globally and by country/region, giving important information regarding the possible triggering mechanisms of the recorded landslide events.

In order to address the research hypotheses, additional criteria were specifically examined:

- The location of the landslide in terms of whether it occurred in a rural area or an urban centre.
- The triggering of the landslide in relation to monsoon rainfall, the occurrence of a tropical cyclone, or seismic shaking.
- The occurrence of the event in relation to land degradation such as deforestation or changes in farming practices.
- The occurrence of the landslide in relation to relevant human/social factors or processes that might have played a role in causation or triggering (examples include, quarrying or road construction).

3.3 Locating the landslides

In order to produce a map, the landslides needed to be spatially referenced with respect to latitude and longitude. Having undertaken a reconnaissance study, it was discovered that while highly detailed electronic maps exist for certain countries and regions, digital maps at the scale required were not available for the entire globe. The latitude and longitude were therefore determined using an electronic gazetteer and atlas. The Falling Rain Genomics online global gazetteer (1996-2004) is a global index of 2.9 million settlements located outside the USA. The gazetteer also provides detailed locational information for all states within North America and was found to be the most comprehensive data source available. Some towns/villages that did not feature within the gazetteer were located using the Encarta electronic atlas (2005) which features 1.8 million places worldwide.

The specificity of the locations varied significantly throughout the database. This was largely due to the nature of the landslide inventory and the complexity associated with its compilation. This resulted in some ambiguity attached to early entries, with a minority of the recorded events being located simply by country. In order to develop a workable database, an attempt was made to determine more detailed locational information. If this was not possible, the landslide remained in the database for statistical analysis but was not mapped. For other landslides a region, province, town or village was listed. The aim was to locate the slides as precisely as possible; however many small villages and towns did not feature within the Gazetteer or atlas. In this instance the landslide was located to the nearest town or city and this was highlighted within the database. For example:

Taldybulak, Talgar district, 20 km east of **Almaty**, Kazakhstan

(The slide was located in Almaty within 20 km of the precise landslide location).

While more detailed 1:25,000 scale paper maps were available for various regions, it was decided these would not be used. This was largely due to the time constraint as >700 landslides had to be located and using paper maps was time consuming. In addition, the available map archive did not provide entire global coverage. Multiple events have been located where possible, however in some cases multiple landslides were triggered by one across a vast area (province-wide or even countrywide) making individual fatal events impossible to locate. In total 72% of the recorded landslide events were located.

A further problem encountered related to the variations in the spelling of place names. This was one of the clear advantages of using the electronic Gazetteer that listed all variations in spelling. For example Huiyuan can be spelt as:

Hui-yüan-ch'eng
Hweiyan
Hweyüan
Hui-yuan-ch'eng
Ili
Hweyuan

For the purpose of locating the landslides it is necessary to consider the precision of the spatial coordinates stored within the database (Theobald, 2003). At the equator each degree of latitude measures 111,95 m. Specifying the location to the nearest second is therefore precise to within ± 30.8 m at the equator (table 3.1). This distance decreases when moving away from the equator to higher latitudes. The Falling Rain global gazetteer locates places to the nearest second (~3 m). However, the precision with which the landslides could be located depended largely on the quality of the original data. It should be noted that the precise landslide location was not provided within the database, but simply a name of the place where the fatal mass movement occurred. Locating this place to within ~30 m did not mean the landslide was located to the same degree of accuracy.

Table 3.1 Precision of latitude and longitude measurements (adapted from Theobald, 2003).

Precision	**Distance / m**
Degree	111,195
Minute	1,853
Second	30.8

3.4 Ground truthing

In order to validate and determine the accuracy of the landslide locations within the database, a ground truthing exercise was undertaken in Taiwan. GPS measurements were taken using a hand held global positioning system at nine fatal landslide sites across central Taiwan. While it was recognised that nine landslides is a particularly small sample, distances between landslide sites and time constraints meant it was only possible to visit sites within a certain area.

Despite an awareness of variations in the accuracy of GPS measurements, for the purpose of this study the reference or ground data collected was assumed to be an accurate representation of reality (Congalton and Green, 1999; Khorram, 1999). Variations of 15 metres in locational accuracy were regarded as insignificant when working at the global scale. In some cases the landslides were difficult to locate within the field; for example the small rock fall that killed two people in their car in A-li-shan. An attempt was made to look for evidence of fatal landslide activity and instability (figure 3.1) including clues such as the presence of ghost money which is a symbol of death. A further problem related to where the GPS readings were taken. For some landslides the GPS reading had to be taken at the road side but for others GPS readings could be taken where the displacement occurred. In some cases landslides covered extensive areas (for example the 1999 Ts'ao-Ling landslide (figure 3.2) with an estimated debris volume of 125 million m^3 (Lee, 2000)). While there was an appreciation that the GPS reading would change depending on where the reading was taken, the position of the GPS was largely influenced by issues of safety and accessibility to the landslide sites. For sites where more than one reading was taken, the most central point was used.

Figure 3.1 A fatal landslide event along the Route 21 highway, near Shenmu, Chenyulan Stream area, Central Taiwan.

Figure 3.2 The fatal Ts'ao-Ling landslide, Taiwan.

Latitude and longitude measurements from the gazetteer were compared to the GPS readings collected for the nine fatal landslide sites visited in central Taiwan. Five of these landslides were known to have been triggered by Typhoon Herb in 1996 and were all located along the same ~20 km stretch of highway in the Chenyulan Stream area (Lin and Jeng, 2000). The nearest village/town to the individual landslide sites located by the gazetteer was Shenmu where a fatal landslide had also occurred in 1996 (Lin and Jeng, 2000). The five fatal landslides were therefore all assigned with the same gazetteer location. It was therefore known that some of these fatal landslides would be up to 20 km from their precise location, a situation similar to a number of landslides within the database.

In order to determine the locational accuracy of the landslides determined from the gazetteer, all latitude and longitude values were converted to the UTM (Universal Transverse Mercator) system using an online spreadsheet converter (Dutch, 2005). UTM grids are created by laying a square grid on the Earth making it possible to calculate the distance between two locations. The results are illustrated in tables 3.2 and 3.3.

Table 3.2 Converting the latitude and longitude to UTM (the places highlighted were located using the electronic gazetteer).

Landslide	Gazetteer E	Gazetteer N	GPS E	GPS N
Shenmu	717306.171	7393579.666	716732.154	7391218.633
Junkengo, **Shenmu**	717306.171	7393579.666	717917.287	7371874.927
Junken Bridge, **Shenmu**	717306.171	7393579.666	718441.899	7372851.813
Fonchu, **Shenmu**	717306.171	7393579.666	716830.848	7380692.587
Tonfu, **Shenmu**	717306.171	7393579.666	715807.417	7390062.935
Ts'ao-Ling	735683.890	7389632.623	736764.004	7389769.041
Chu-Feng Ershan	723041.475	7360656.196	719264.493	7348711.726
A-li-shan	723154.675	7397584.629	725911.090	7399665.867
Hoping, Taichung	715252.064	7324583.128	727243.898	7338246.391

A comparison of the results shows there to be a wide variation in locational accuracy from within 1 km to >20 km. Although there are clearly inaccuracies generated by the utilisation of a gazetteer, these were felt to be minimal when working at a global scale with reduced spatial resolution.

Table 3.3 Calculating the distance between the GPS and the gazetteer landslide locations

Landslide	**Easting Difference**	**Northing Difference**	**Distance between points / m**	**Distance between points / km**
Shenmu	574.0171101	2361.033329	2429.809462	2.4298095
Junkengo	-611.1151551	21704.73958	21713.3411	21.7133411
Junken Bridge	-1135.727767	20727.85377	20758.94505	20.7589451
Fonchu	475.3232216	12887.07933	12895.84219	12.8958422
Tonfu	1498.754598	3516.731711	3822.78266	3.8227827
Ts'ao-Ling	-1080.113667	-136.417745	1088.694326	1.0886943
Chu-Feng Ershan	3776.982393	11944.46969	12527.40804	12.5274080
A-li-shan	-2756.415687	-2081.23773	3453.893154	3.4538932
Hoping	-11991.83486	-13663.2635	18179.35291	18.1793529

The landslides were initially defined in decimal degrees because locational information in the form of degrees, minutes and seconds is not helpful in spatial analysis (Evans and Cox, 2001; *unpublished*). Decimal degrees have the advantage that they can be stored in one field within a database, making it much easier to plot these data using computer based programmes. For the majority of landslides located using the gazetteer, the latitude and longitude were available in decimal degrees but conversion was required for landslides located using the atlas. Basic editing was also undertaken during and following data input for the routine checking of obvious errors. This provided the opportunity to correct mislocations (Evans and Cox, 2001; *unpublished*).

3.5 Creating a global spatial landslide inventory

To analyse the global distribution pattern of landslide activity, a spatial inventory (Dikau *et al*, 1996) was created using a Geographical Information System (GIS). GIS was selected due to its functional capabilities which enable the effective management of large volumes of complex, spatially referenced data. This chapter will not describe the detailed software functionality of the selected ArcGIS programme, but will briefly outline the methodology adopted to generate the spatial landslide inventory.

1. *Data input* – the data were stored in a simple Excel spreadsheet which was subsequently converted into a format that could be used by the GIS (Aronoff, 1989). This simply involved selecting the required data (date, landslide location, latitude and longitude, number of fatalities and identified trigger) and saving the spreadsheet as a database file. The database automatically assigns each entry with an individual attribute number allowing queries to be made about these data. The database was converted into a point feature shapefile (.shp) using ArcCatalog based upon the XY (latitude/longitude) table database. This retained the details of each landslide as attribute data. The spatial reference of the input coordinates was set on the standard WGS 84 datum, as this format is commonly used for the presentation of other global spatial datasets.

2. *ArcMap* – Having created a shape file, the landslide point data was added to a map file (.mxd) in ArcMap (figure 3.4), for display and spatial analysis.

3. *Data output* – A range of base maps and secondary datasets were added into the GIS and the landslide point data overlaid (figure 3.4). A series of thematic feature maps were then generated to display the geographical distribution of the fatal landslide events in relation to a range of physical and human parameters.

In an attempt to address the concerns over the ambiguity of the landslide locations, only landslides located to within 100 km of their precise location were mapped, a dataset of 528 landslides. While the majority of the landslides were located far more precisely, this was considered accurate enough given the global scale of the research being undertaken, especially when considering the spatial scale, extent and variability of the global factors which influence landslide distributions.

The level of locational accuracy was based upon an arbitrary classification. If the village, town or city where the landslide occurred could be located these events were included. However, for landslides located by the nearest recognisable village, town or city, the accuracy of the location required more detailed consideration. In some cases the level of accuracy was clear from the location description given, for example a landslide was located in Wabane, Southwest Cameroon, 400 km from Yaounde. In this instance if the village could not be located but the town could, the distance from the landslide was known and if this distance was within 100 km the landslide was included. Findings from the reconnaissance study undertaken suggested that news and aid agency reports tended to locate landslides in relation to nearby towns of relatively close proximity unless stated otherwise or the landslide occurred in a particularly rural location some distance from another settlement. In such instances these landslide events were excluded. An attempt was made

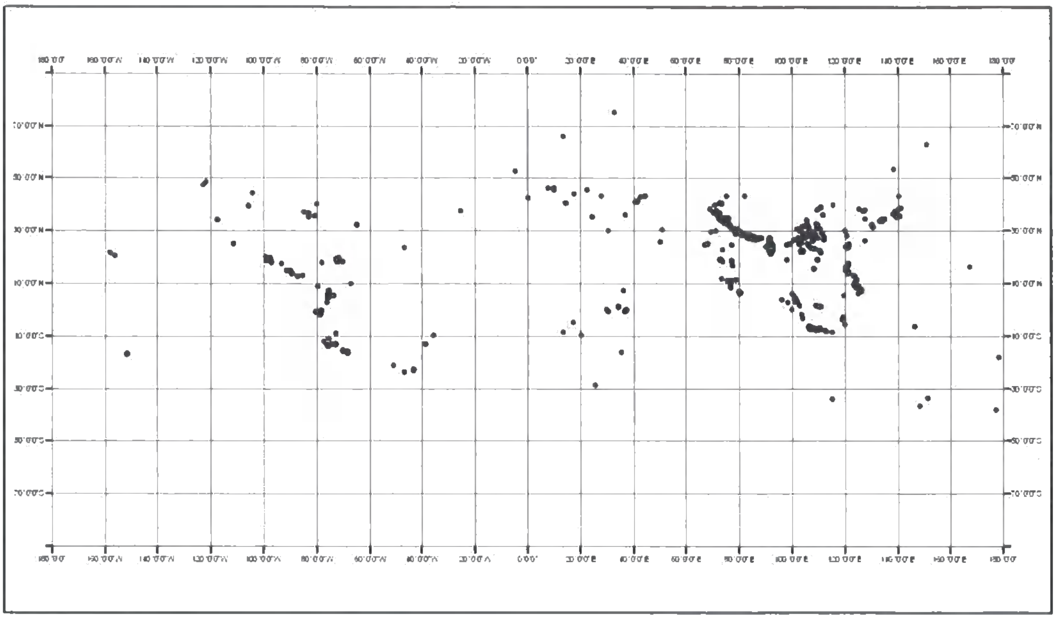


Figure 3.3 The landslide point data on an empty grid.

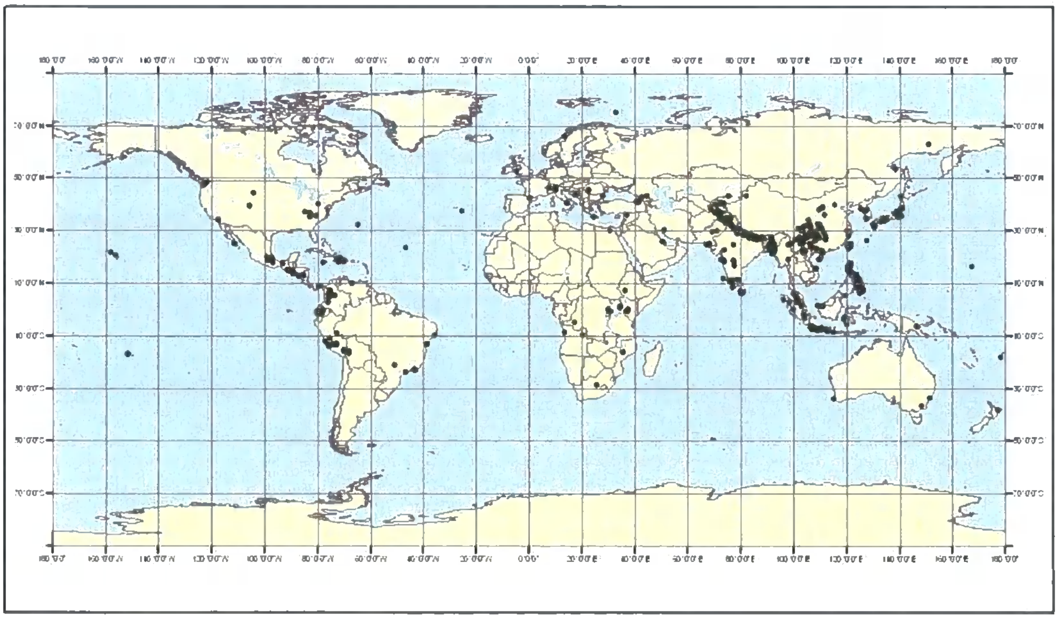


Figure 3.4 The fatal landslides located on a basemap of the world. (Basemap: ESRI, 1999).

to quantify the locational accuracy of each landslide, however due to the nature of the information this proved impossible.

3.6 Analysing the global distribution of landslides in relation to potential human and physical causative factors

This study used the spatial overlay function of the GIS to examine the correlation of landslides and their causative factors (Zhou *et al*, 2002). GIS has clear advantages over manual map production (Dikau *et al*, 1996). Primarily it can be used to overlay information building up a series of layers for example, landslide distribution, global topography and population density which allow both qualitative and quantitative assessments to be undertaken. These layers can then be combined into a single image allowing the analysis of one variable against another. While multivariate analysis is possible, this research focused upon univariate analysis, whereby the global fatal landslide distribution was analysed in relation to individual physiographic, climatic and human based parameters (Small and Cohen, 1999).

Having identified the physical and human/social causative factors of mass movement (including global topography, seismic activity, precipitation and population density) it was necessary to obtain secondary datasets for use within the GIS. When selecting the data, two issues must be considered; the resolution and quality of the data being used, and secondly the importability and usability within ArcGIS.

The resolution of the data is particularly important when analysing spatial relationships. Population density, relative relief and mean annual precipitation data have all been spatially averaged using some form of statistical interpolation from either point measurements or surveys, or from analysis of various forms of remote sensing data. This is then re-sampled to a desired resolution required to generate a raster map (where spatial data is expressed as a matrix of cells) (Duncan, *pers comm.*). The resolution is commonly a balance between the clarity of the image and the practicality of the file size. For example, a relief grid may be generated from digital elevation data and the calculated difference in elevation between a number of cells. Mean annual precipitation data will be calculated from raw rain gauged measurements collected over a certain area (figure 3.5).

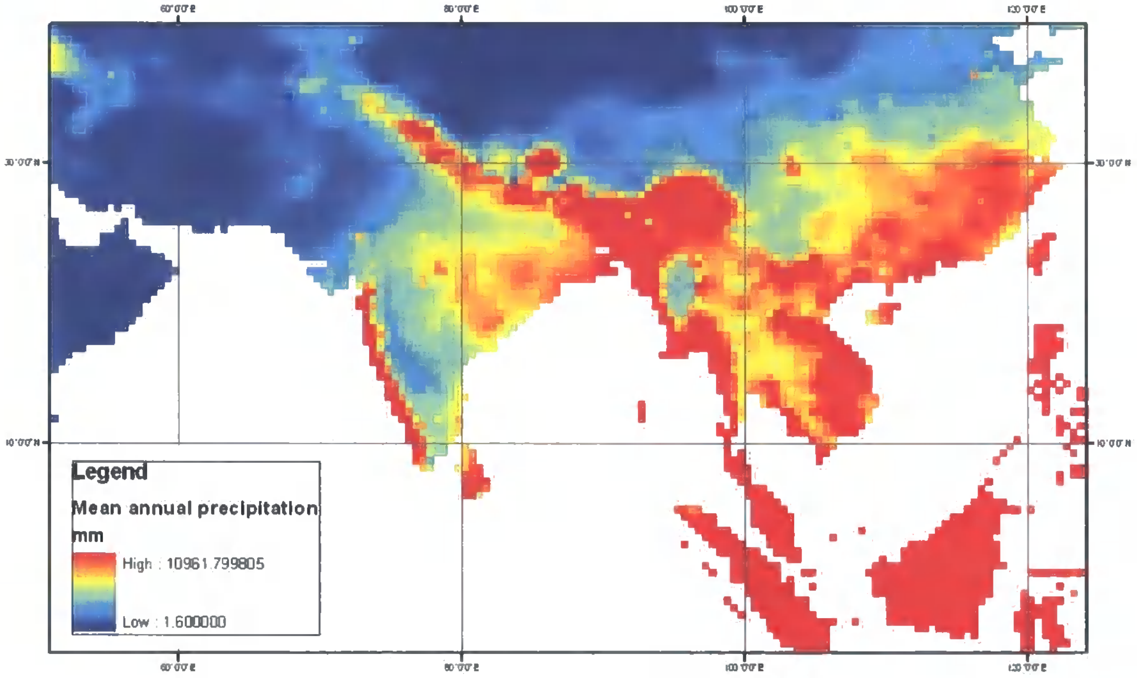


Figure 3.5 A raster map of mean annual precipitation in the South Asian region. (Rainfall data derived from Willmott *et al*, 1998; created into a raster image by Duncan, *pers comm.*).

When analysing the spatial relationship between landslides and the selected parameters the resolution of the parameter data was often greater than the landslide data. For example, the relative relief data have a resolution of 2.5 km, while some of the more poorly located landslides were potentially located up to 100 km from their actual location. As a result some of the landslides may be associated with incorrect parameter values, or indeed located in cells which neighbour their actual positions. However, while it is necessary to have an awareness of such issues, this research was concerned with analysing the broad spatial patterns and controls of fatal landslide occurrence on a global scale. It was also found that the nature of the global datasets, in general, show a transition from extremes, from say an area of high rainfall to an area of low rainfall, rather than a sharp step in the data value in neighbouring cells, which is potentially a result of the way in which the datasets are derived. Therefore mis-location of a single, or small number of landslides within this landslide database would have little bearing of the statistical significance of any result obtained. Analysis of this variation induced by location, relative to the other uncertainties within the database would help to qualify this further, but is beyond the scope of this study.

3.7 Spatial analysis

A fundamental way of analysing the relationship between landslides and their causative factors is to examine the distribution of landslides in relation to each physical and human/social factor (Carrara *et al*, 1991). This method was adopted by Zhou *et al* (2002) in their landslide research on Lantau Island, Hong Kong. In the study reported here the global distribution of landslides was analysed in relation to the following:

- Global population density
- Global plate boundaries

- Mean annual precipitation
- Global relative relief
- A global erosion index

The Geography Network houses a suite of datasets that are accessible within ArcGIS. These include global population statistics compiled by ESRI using data from national population censuses and the United Nations demographic year books. For other data sets alternative sources were sought. For example, global precipitation data and relative relief were provided by Duncan (*pers comm.*) from the Department of GeoSciences, University of Massachusetts (full details of the derivation of these datasets and their format can be found in section 4.3.2).

3.8 Evaluating the completeness of the landslide database

The final stage of the methodology involved evaluating the completeness of the landslide database. Phase one was a simple desk top study comparing the landslide database with other established landslide inventories including the EM-DAT Disaster Events Database compiled by the Centre for Research on the Epidemiology of Disasters, University of Louvain, Belgium and the global inventory compiled by Alexander (2005). Phase two investigated a series of case studies including China, Iran and fieldwork undertaken in central Taiwan. The reliability of the database for Taiwan was discussed during interviews with academics at the National Taiwan University in Taipei. Visits were undertaken to sites affected by landslides following Typhoon Herb in 1996, the Chi-Chi earthquake in 1999 and Typhoon Toraji in 2001. The aim of this fieldwork was to evaluate the current database, to identify where fatal landslides occurred and to develop an understanding of the triggering mechanisms of fatal landslide events.

4.1 INTRODUCTORY ANALYSIS

4.1.1 Introduction

The landslide dataset includes 642 fatal landslide events recorded between 1st January 1994 and 31st December 2004. These events resulted in 13,011 fatalities. In addition, 79 multiple mass movement events were recorded, increasing the death toll by 40,000 fatalities. In total, the dataset recorded 53,011 fatalities, an average of ~4,819 deaths per year.

4.1.2 Spatial Analysis

Figure 4.1 illustrates the spatial distribution of all fatal landslide events that have proven possible to locate to within 100 km of their precise location. Mass movement events were recorded in 81 countries throughout Africa, the Americas, Asia, Australasia, Europe and the Middle East. The events predominantly clustered in Asia, along the Himalayan Arc, through the southern and central provinces of China, along the Indonesian archipelago, in the Philippines and in Japan.

4.1.3 Landslide fatalities

Figure 4.2 illustrates the number of individual landslide events recorded per year and the number of associated fatalities. There was a dramatic increase in the number of recorded events between 2002 and 2003, with 63% of recorded landslides occurring in 2003 and 2004. Since September 2002 the landslide database has been compiled on a daily basis, generating a relatively complete catalogue of fatal landslide events. In addition, there has been considerable improvement in the quality and availability of data on disasters in recent

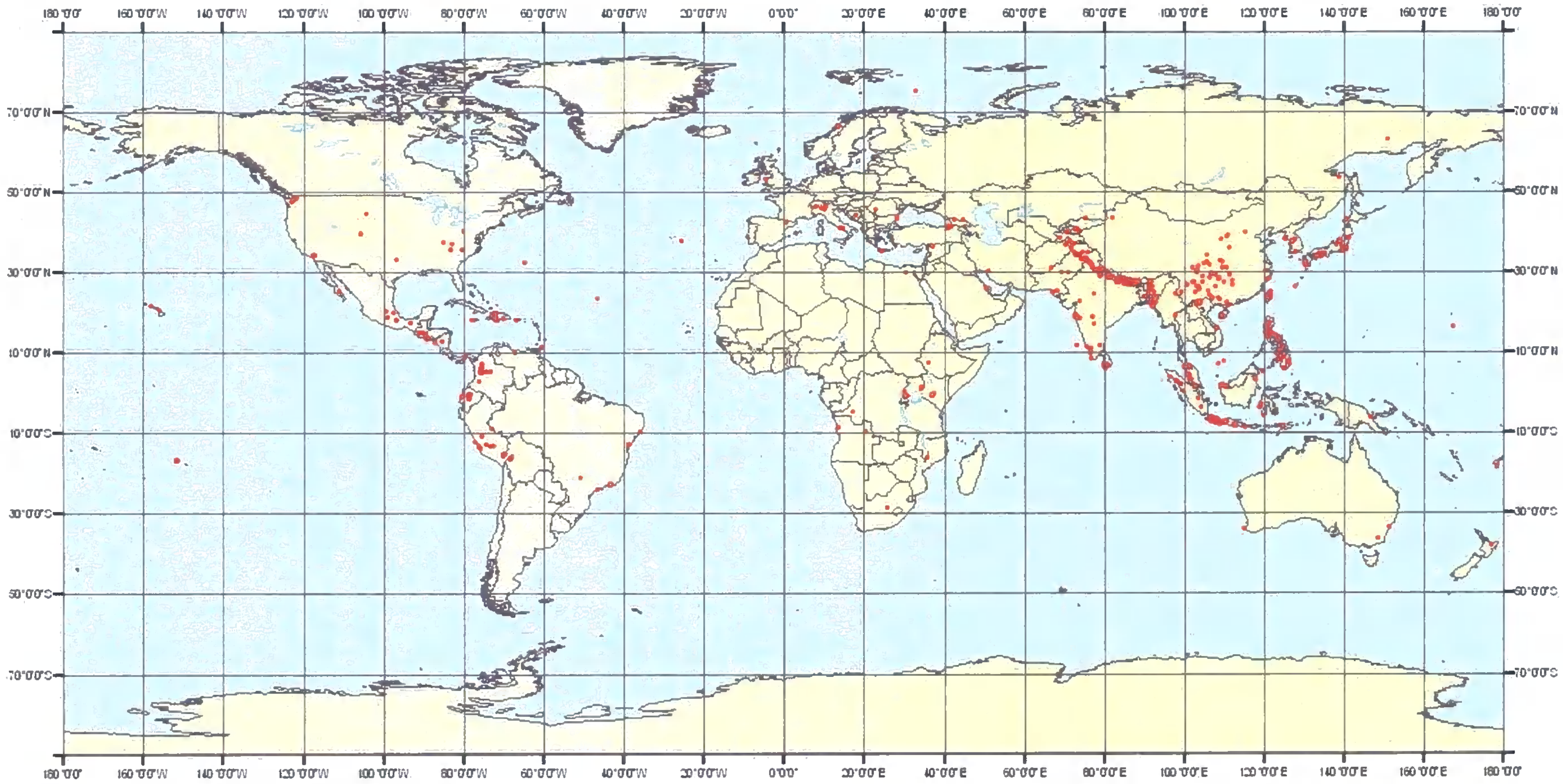


Figure 4.1 A spatial inventory of fatal landslide events (author's dataset). Landslides have been located to within 100 km of their precise location. Each fatal landslide is indicated by a red dot. (Basemap: ESRI, 1999).

years (Alexander, 1997). However, when compiling the long term inventory a decay effect was observed as information on landslide events became increasingly difficult to obtain (Petley *et al*, 2005).

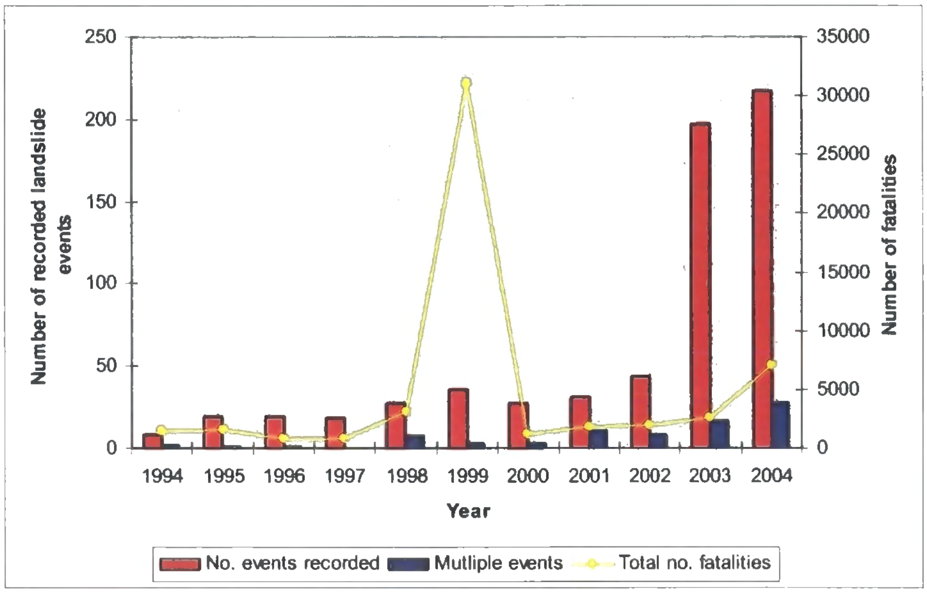


Figure 4.2 The number of fatal landslide events and the number of related fatalities recorded within the landslide database between 1994 and 2004.

In an attempt to examine the change in the occurrence of landslide fatalities with time, the dataset has been clipped to exclude events with <10 and >1,500 fatalities. Collecting information and data about small scale events is often difficult, with a large percentage of events going unreported due to their relatively low impact (Petley *et al*, 2005). While these events were recorded in the 2002-2004 subset, the retrospective database did not pick up these events. The lower boundary has therefore been set using criteria from the established Centre for Research on the Epidemiology of Disasters database. In addition, very large events occur so infrequently that they represent outliers in a data set of such a relatively short duration (Petley *et al*, 2005). Figure 4.3 plots these data accompanied by an exponential trend line. These data show an overall rise in the number of landslide related deaths per year. In addition, there is a clear increase in the number of fatalities from 1999. Prior to this, the pattern is far less clearly defined. The most dramatic increase of 1,425 fatalities occurred between 2003 and 2004. One possible explanation for this observed trend relates to the increasing availability of data and the better reporting of landslide events in recent years.

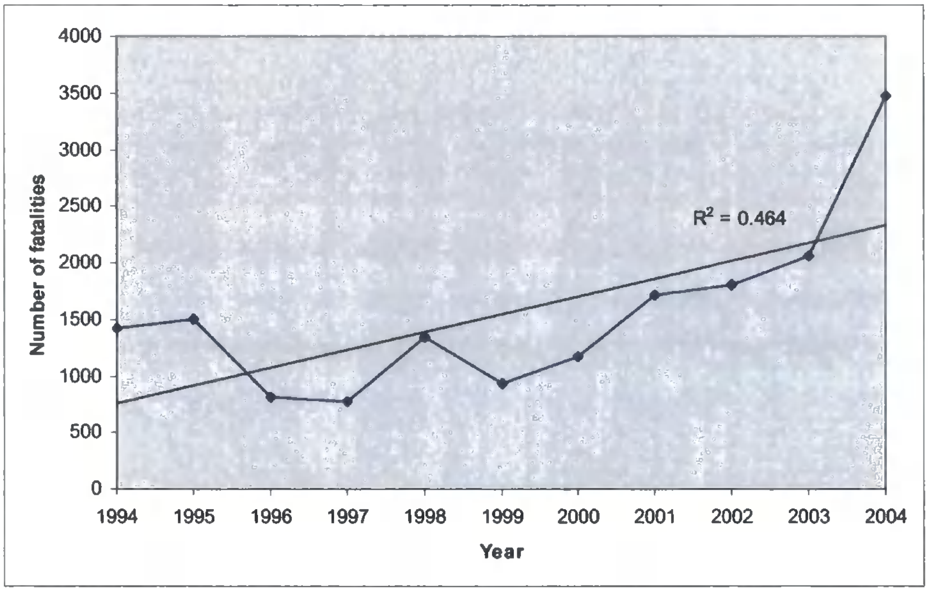


Figure 4.3 The number of landslide fatalities per year resulting from moderately-sized events.

4.1.4 Magnitude-frequency analysis

When analysing the magnitude-frequency pattern of the dataset, multiple landslides (where the number of fatalities per event was unknown) were excluded. The remaining landslide events followed the standard magnitude-frequency relationship for natural hazards (figure 4.4). 51% of the landslide events recorded resulted in ≤ 5 fatalities. However, these events accounted for only 5% of the total number of recorded fatalities. In comparison, the rare, exceptionally high magnitude events characterised by >1001 fatalities were seen to cause the majority of fatalities.

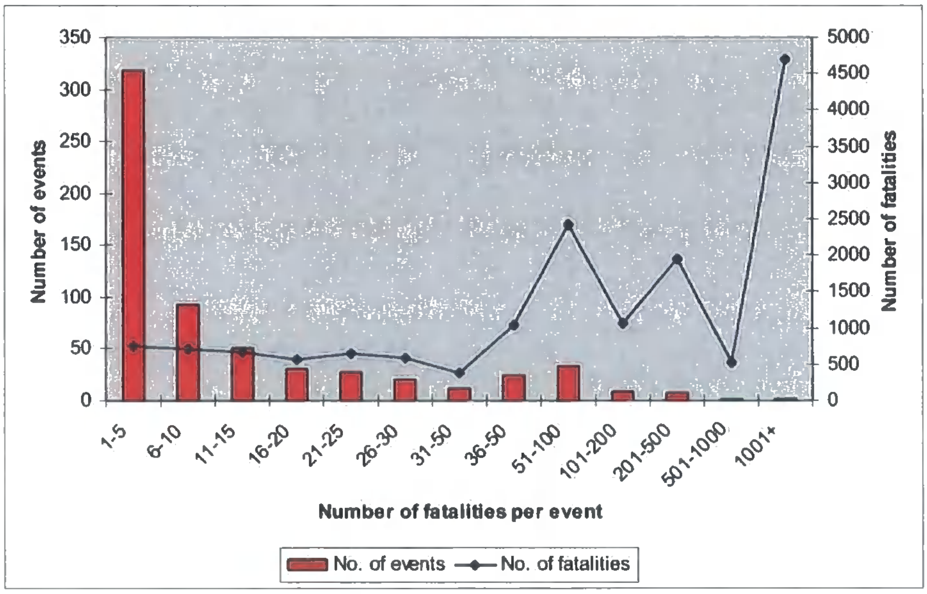


Figure 4.4 Magnitude-frequency relationship for the number of deaths per landslide event. The graph excludes multiple landslide events where the number of fatalities per event was unknown.

4.1.5 Types of Mass Movement

While the type of mass movement has not been recorded for all landslide entries within the landslide database, analysis of the available information suggests the high numbers of fatalities were associated with multiple landslides, debris and mudflows. Events characterised by >1,000 fatalities included the multiple landslides in Vargas, Venezuela, the debris and mudflows in Haiti and Colombia and the volcano flank collapse in Nicaragua. However, mudflows and multiple landslides were also associated with low numbers of fatalities; for example, the mudflows in Thailand and Tajikistan in May 2004 which resulted in 8 fatalities. Rockfalls were generally associated with fewer deaths per event, with 71% of events resulting in <10 fatalities. Two rock avalanches were recorded; the first in the Mont Blanc Range in Italy in 1997 killing 2 people, the second in Dharchula, India in 1998 which resulted in 210 fatalities. Similarly, mudslides and landslides were seen to vary in magnitude and impact, with fatalities ranging from 1 to >500 deaths per event. These findings illustrate the heterogeneity of the impacts of mass movement.

4.1.6 Landslide Triggers

A trigger has been identified for 75% of the recorded landslide events. 87% of those landslides were triggered by high intensity or prolonged precipitation events often associated with the annual monsoon or tropical cyclones. These rainfall induced landslides caused 94% of the recorded fatalities. Earthquakes were a comparatively infrequent trigger, initiating only 4% of the fatal mass movements, which resulted in 4% of the recorded fatalities. Other physical triggers included glacial collapse and heavy snow which triggered 0.9% of events and 0.3% of fatalities. Two recorded events were associated with volcanoes, the flank collapse of Casita volcano in Nicaragua, triggered by heavy rains from Hurricane Mitch, and a landslide on Chichontepec volcano in El Salvador triggered by a magnitude 6.6 earthquake. Additional events within the database were associated with mining and excavation work, road construction and embankment failure, triggering 7% of landslide events and resulting in 0.7% of fatalities.

4.1.7 Regional Analysis

Analysing global averages of fatality data often masks the vulnerability of certain nations, as noted by Bilham (2004) with reference to earthquake disasters. With this in mind regional and sub-regional analyses have been undertaken. Table 4.1 and figure 4.5 provide a regional breakdown of fatal landslide events (see Appendix 2 for individual countries). The American region furnished the highest death toll, accounting for 76% of the total fatalities. The sub-regional breakdown shows that the highest number of fatalities occurred in South America, dominated by the 1999 Venezuelan landslides.

Table 4.1 Regional breakdown of landslide disasters between January 1994 and December 2004.

Region	Sub-region	No. of landslide events	No. of multiple landslide events	Total no. of fatalities
Africa	North	1		230
	Sub-Saharan	27	1	391
	South Africa	1		34
		29	**1**	**655**
Americas	North	20		51
	Caribbean	12	3	4555
	Central	15	2	2772
	South	56	11	32950
		103	**16**	**40328**
Asia	South	183	21	4087
	Central	22	1	631
	East	140	21	2995
	South East	129	12	3480
		474	**55**	**11193**
Australasia	Australia and New Zealand	9	1	177
	Pacific Islands	3	2	36
		12	**3**	**213**
Europe		**21**	**2**	**402**
Middle East		**3**	**2**	**220**

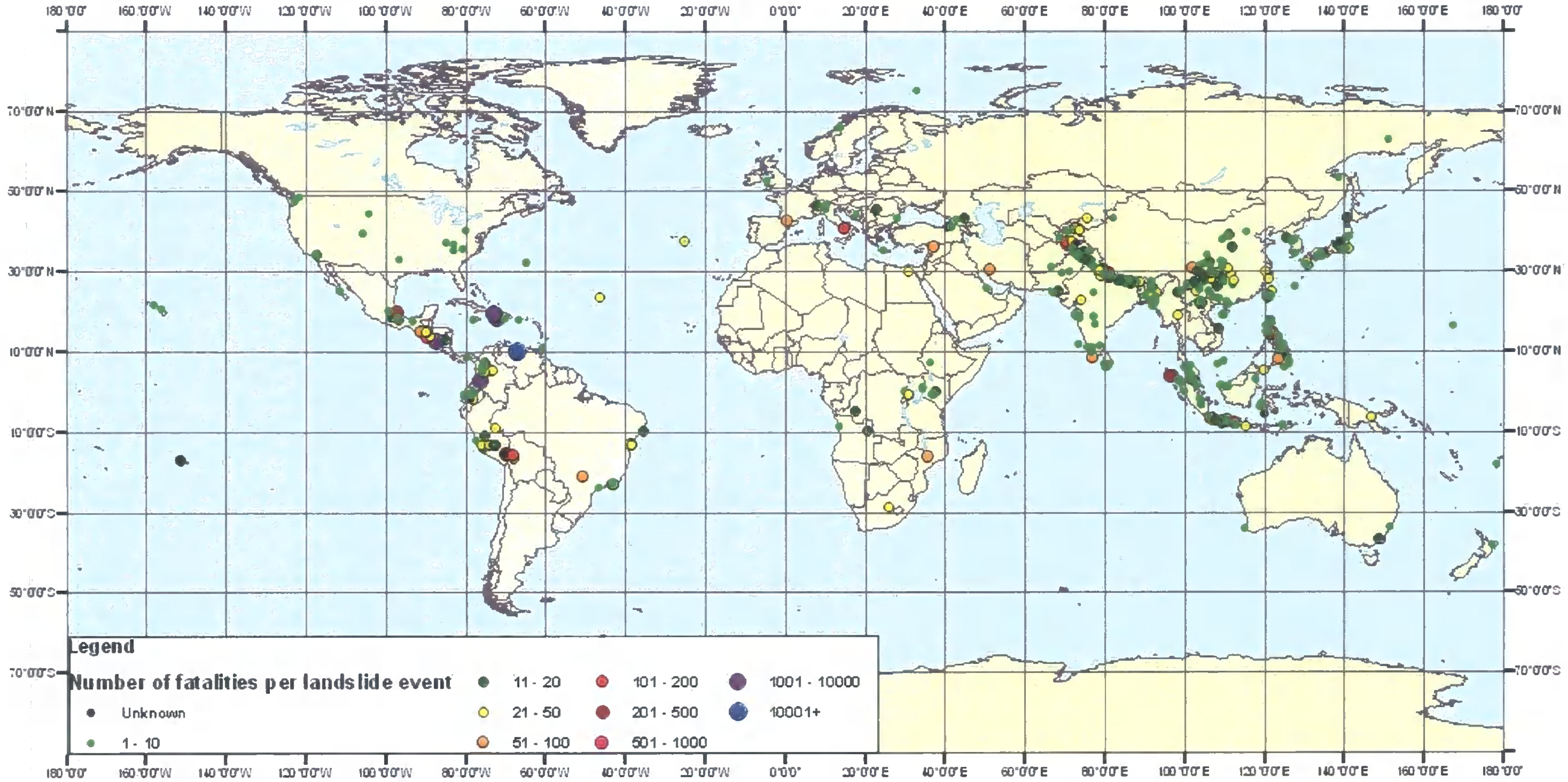


Figure 4.5 The number of fatalities per landslide event (author's dataset).

(Basemap: ESRI, 1999).

The number of fatalities was also high in Asia (Figure 4.6) with 21% of the recorded fatalities occurring within this region. The South Asian sub-region emerged with the highest death toll, accounting for 37% of fatalities within the region, followed by East Asia with 30%.

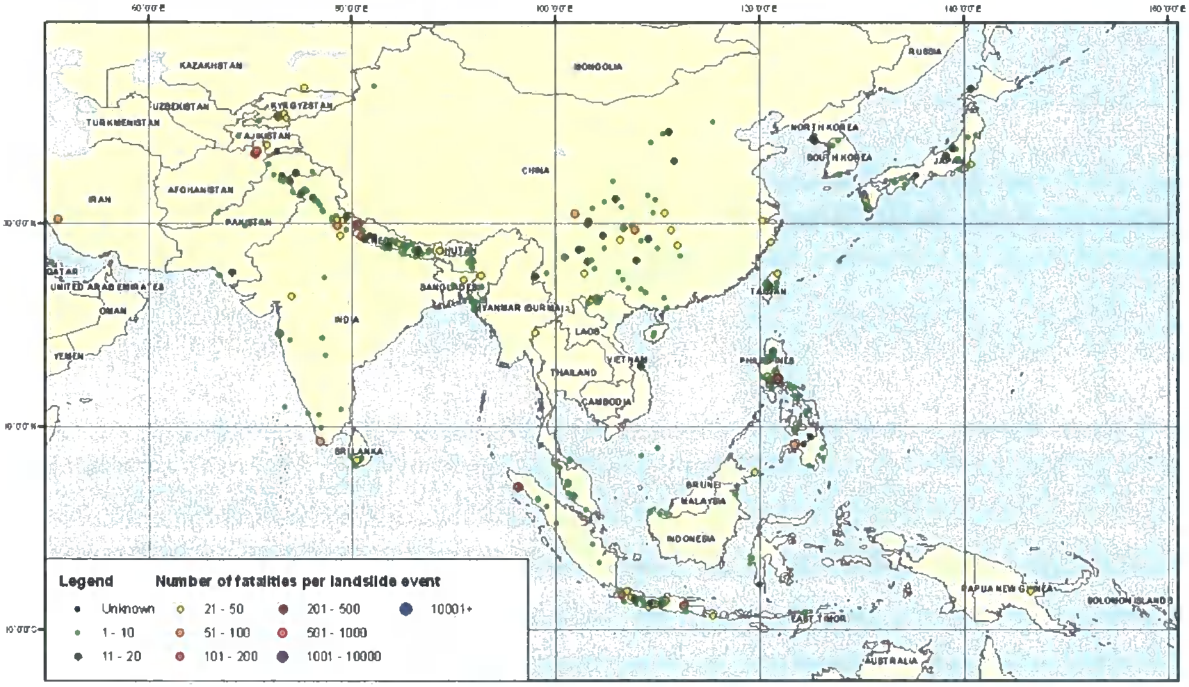


Figure 4.6 A regional breakdown showing the number of fatalities per landslide event for Asia (Basemap: ESRI, 1999).

4.1.9 Multiple landslide events

79 multiple landslide events were recorded within the database. 70% of these events occurred within Asia and 20% in the Americas. Despite the higher frequency of events within Asia, the death toll was approximately 13 times greater in the Americas which experienced 35,174 landslide induced fatalities. These statistics can be attributed to two exceptionally high magnitude multiple mass movement events, the most significant of

which occurred in Venezuela during 1999 when heavy rain triggered multiple landslide events resulting in ~30,000 fatalities. Haiti experienced two relatively high magnitude landslide events, including mudflows triggered by high intensity precipitation in May 2004 that resulted in ~1500 fatalities and a similar event in September of the same year resulting in a further 3,006 deaths. The landslide database suggests that while the frequency of fatal landslides was greater in Asia, low frequency but exceptionally high magnitude multiple mass movement events were seen to occur in the Americas. However, to affirm these findings it would be necessary to look beyond this eleven year dataset.

Summary

This sub-chapter has outlined the broad trends and spatial patterns observed in the distribution of fatal landslide events recorded within the landslide database. The following conclusions have been made:

1. The frequency of fatal landslide events in the database shows an increase with time. However, these findings may be attributed to better reporting and recording of events which has enabled the compilation of a more comprehensive dataset.
2. The landslides recorded fit the classic magnitude-frequency relationship characteristic of hazard events (Alexander, 2005).
3. The highest numbers of fatalities (>1,000 fatalities) were associated with multiple landslides, debris and mudflows. Rockfalls were generally associated with <10 deaths per event, while mudslides and landslides were seen to vary in magnitude and impact with fatalities ranging from 1 to >500 deaths per event.
4. The dominant triggers of fatal landslide events were high intensity and prolonged precipitation, which triggered 87% of the recorded mass movement events.

5. The American region furnished the highest death tolls accounting for 76% of the total fatalities, while 21% of fatalities occurred in Asia.
6. Asia's landslide inventory was dominated by high frequency, low magnitude events, while high magnitude, low frequency events characterised the Americas.

4.2 ANALYSING THE SPATIAL DISTRIBUTION OF FATAL LANDSLIDE EVENTS: THE HUMAN PERPECTIVE

4.2.1 Introduction

This sub-chapter attempts to address the complex issue of human vulnerability and the impact of economic development upon landslide related fatalities. The relationships between population density, population growth and fatal landslide occurrence have been examined and comparisons made between the occurrence and distribution of fatal landslide events in urban and rural areas. In addition, the impact of deforestation, agricultural practices and road construction have also been considered, with a view to determining their influence on the magnitude and distribution of fatal landslide events.

4.2.2 Assessing vulnerability

Classifying countries as underdeveloped, developed or developing is contentious, particularly as the term development is fraught with ambiguity and definitions are seen to vary. A number of reports and papers examining the trends in hazard occurrence compare the impact of events in less developed and more developed countries (Hewitt, 1997; Alexander, 1989, 2005; Alcántara-Ayala, 2002; Wisner *et al*, 2004). In an attempt to undertake a similar form of analysis, reference has been made to the World Bank's World Development Indicators Report (2005) which categorises countries by gross national income (GNI) per capita into low, lower middle, upper middle and high income countries (Figure 4.7). An attempt is also made to assess vulnerability (defined by the World Bank (2005) as a households resilience in the face of shocks and the likelihood that a shock will lead to a decline in well-being) based upon a series of indicators including urban formal sector employment, youth employment, children in the labour force and private health expenditure (World Bank, 2005). However, the availability of data varies significantly between countries. The spatial distribution of fatal landslides have therefore been analysed based upon the World Bank's income classification (World Bank, 2005) which provides a crude indication of levels of poverty and deprivation (figure 4.8).

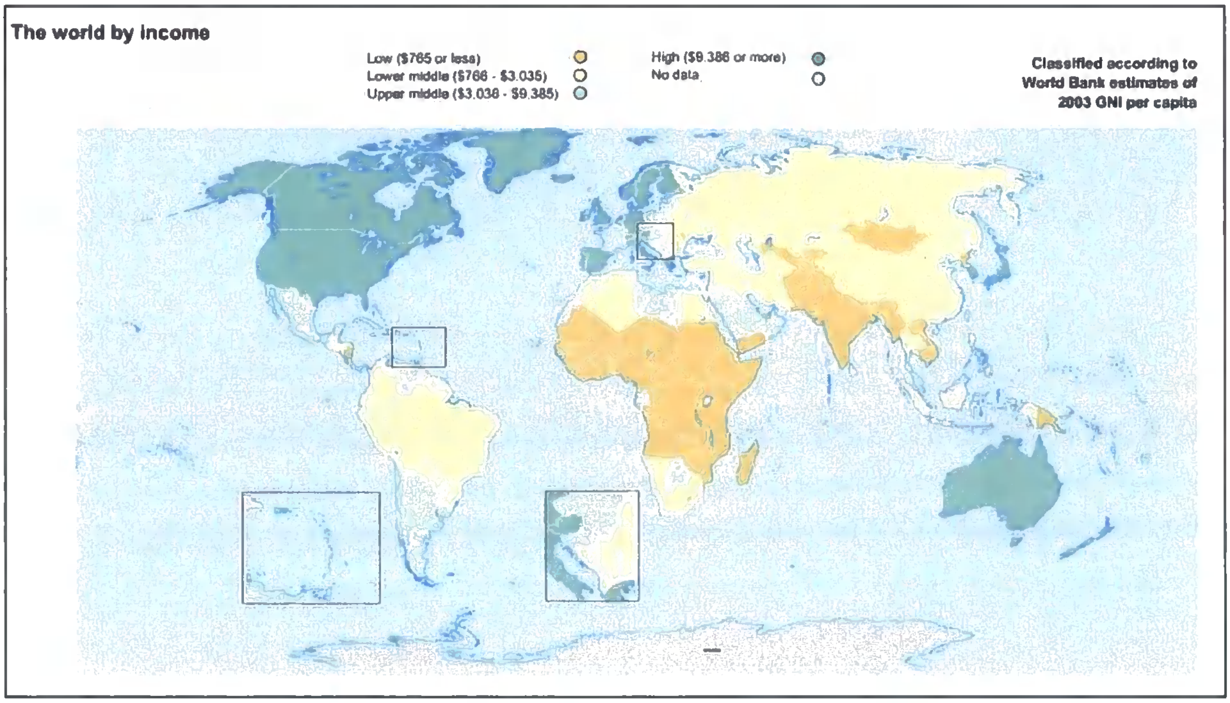


Figure 4.7 The world by income (The World Bank, 2005).

Countries within the landslide database were classified based upon the World Bank's income classification. The results show that fatal landslide events occurred most frequently in lower middle income countries, where 45% of landslide events and 58% of multiple mass movement events were recorded (figure 4.8). Low income countries also experienced a high frequency of fatal landslide activity, with 39% of recorded landslide events and 32% of multiple events occurring within these countries. The number of events recorded for upper middle and high income countries was far lower. 16% of the recorded fatal landslide events and 10% of the multiple events occurred within countries in the upper income bracket. However, it should be noted that the number of events recorded in high income countries was more than three times greater than countries classified with an upper middle gross national income per capita. These findings differ from the hypothesised model.

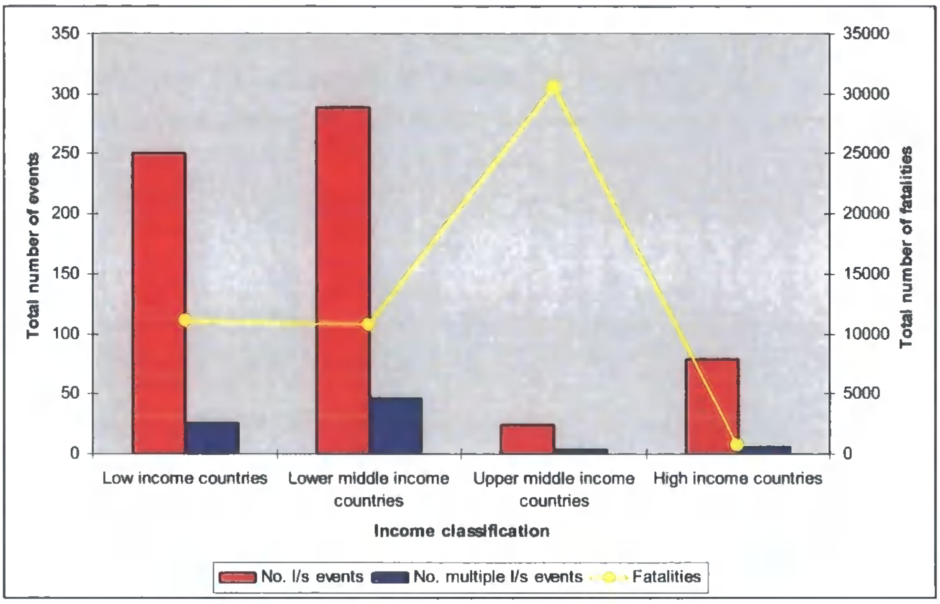


Figure 4.8 The number of fatal landslide and multiple landslide events recorded and the total number of fatalities in low, lower middle, upper middle and high income countries.

The fatality breakdown shows an interesting and unexpected trend, with the highest number of fatalities being recorded within upper middle income countries associated with the lowest recorded incidence of landslide activity. 21% of recorded fatalities occurred in low income countries and 20% in lower middle income countries (a difference of ~348 fatalities). As hypothesised the high income countries furnished the lowest death tolls accounting for 1% of the total recorded. Table 4.2 shows the top twenty countries with the highest recorded fatality totals. These findings suggest that landslide fatalities do not necessarily correlate with the level of economic development of a country and therefore differ from the findings of Alexander (1993, 2005) and Alcántara-Ayala (2002) who observed that global death tolls due to natural disasters were concentrated in developing countries. Instead the relationship appears to be far more complex than the hypothesis suggests.

Table 4.2 The top twenty countries with the highest number of recorded fatalities. The income classification is based upon the World Bank (2005).

Rank	**Country**	**Income classification**	**No. of landslide events**	**No. of multiple landslide events**	**No. of fatalities**
1	Venezuela	Upper-middle		1	30000
2	Haiti	Low	4	2	4519
3	China	Lower-middle	86	17	2250
4	Philippines	Lower-middle	45	6	1823
5	India	Low	76	11	1726
6	Nicaragua	Low	1	1	1694
7	Colombia	Lower-middle	17	4	1479
8	Indonesia	Lower-middle	50	5	1260
9	Nepal	Low	61	7	1201
10	El Salvador	Lower-middle	3		558
11	Afghanistan	Low	4		537
12	Peru	Lower-middle	14		527
13	Brazil	Lower-middle	11	4	517
14	Taiwan	Lower-middle	14	2	487
15	Mexico	Upper-middle	6	1	382
16	Sri Lanka	Lower-middle	6	1	315
17	Kyrgyzstan	Low	7	1	258
18	Morocco	Lower-middle	1		230
19	Bolivia	Lower-middle	2	2	221
20	Japan	High	33	2	208

When analysing the spatial trends in fatal landslide occurrence it is important to consider the time scale over which the data has been collected. Would similar spatial patterns emerge if a longer time series was examined or if more detailed information was available in areas where landslide fatality data is currently sparse? Such factors would undoubtedly influence our understanding of the spatial distribution of fatal landslide events and the associated spatial vulnerabilities. For example, between 1994 and 2004 the landslide fatality dataset is heavily skewed by the mudslide events in Venezuela, highlighting the vulnerability of communities in upper middle income countries in Central and South America. These findings suggest that the occurrence of fatal landslide events is not simply a function of the level of development of a country. If landslide events (and associated fatalities) triggered by the 2004 Indian Ocean earthquake and the fatal mass movement events in 2005 were included in the dataset, the picture would be somewhat different. The Kashmir earthquake in October 2005 triggered extensive landsliding and while the number of landslide related deaths is unknown, in total the earthquake killed >73,000 people (CRED, 2006). In addition, with the exception of Hurricane Stan and Katrina (affecting Guatemala and the USA respectively), the natural disasters associated with the highest numbers of deaths occurred within the Asian region in low and lower middle income countries, affirming the findings of Alexander (1993, 2005) and Alcántara-Ayala (2002). However, as previously noted it would be necessary to examine a longer data set to determine the spatial representivity of the eleven year dataset.

4.2.3 Population density and landslide occurrence

In general there is some logic in contending that there will be a positive correlation between numbers of landslide fatalities and population density. If a landslide occurs within a densely populated area more people are potentially exposed and 'at risk' from the impact of this event. Viewing this model in its most simplistic form, if a landslide occurs within the urban centre of Rio de Janeiro in Brazil, the number of people exposed to the hazard is high, increasing the likelihood of fatalities and injuries. In comparison, if a similar sized event occurred within a sparsely populated part of the High Himalaya, the number of people exposed to the hazard would be comparatively low. While the distribution of landslides is uneven, population growth is occurring in areas that are susceptible to mass movement. These rising global populations will undoubtedly put more people at risk from landslide events, a model based purely on probability of exposure.

Vulnerability is often high where settlements are at their most dense and/or where they are most exposed to the hazards. For example, settlements concentrated at the foot of an unmanaged or poorly engineered slope are particularly susceptible to landslide events (Alexander, 2005). Vulnerability is perceived to be at its greatest when high population densities and high levels of hazard intersect. With this in mind the fatal landslide events have been plotted on a base map of global population density (Figure 4.9).

Landslide events are clustered within south eastern China, India, Japan, Korea and on the island of Java, which are areas characterised by high population densities. However, the spatial relationship observed in figure 4.9 is somewhat misleading. A closer examination of the Asian region (figure 4.10) depicts the clustering of events along the Himalayan arc,

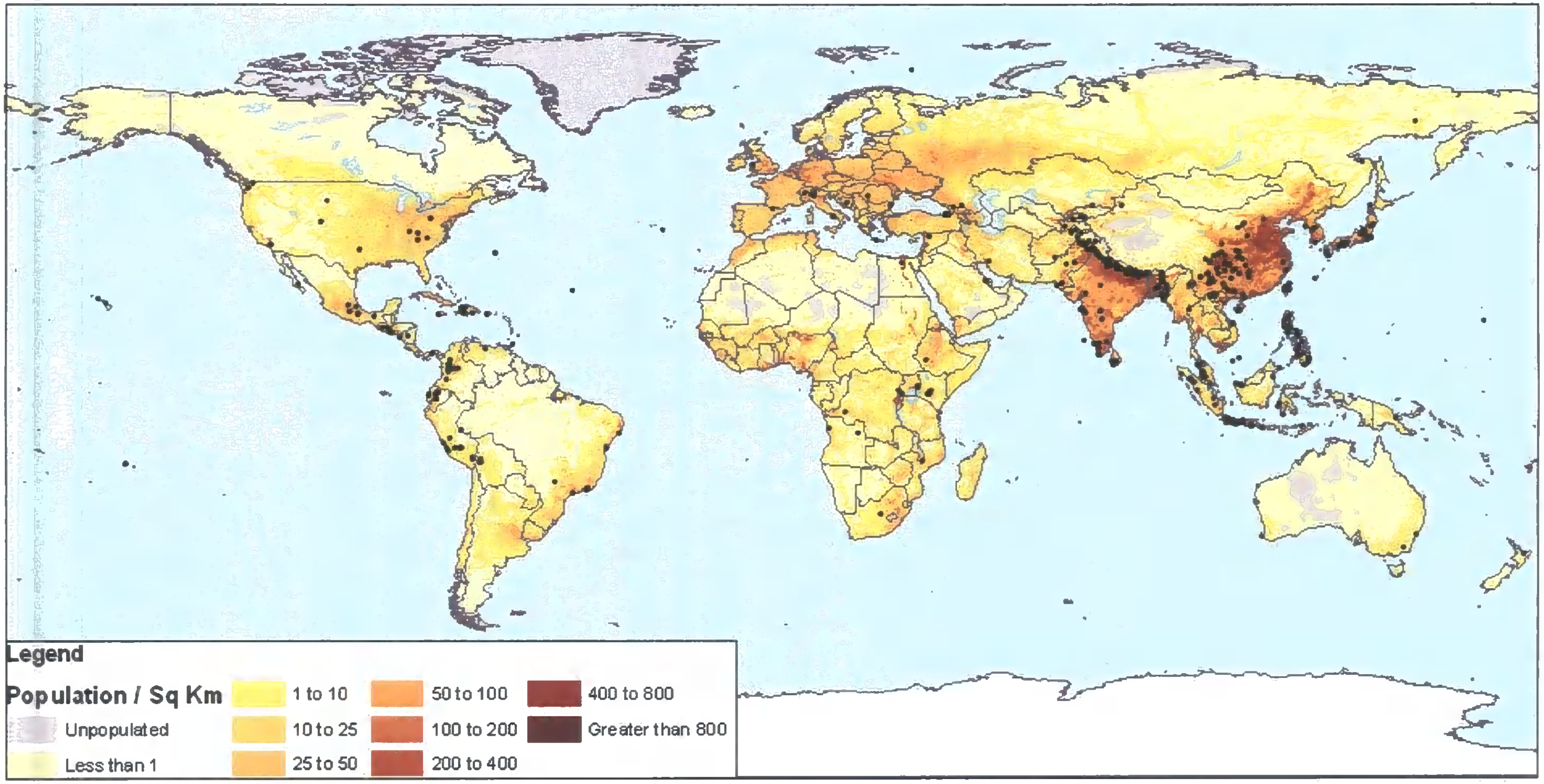


Figure 4.9 Fatal landslide events and world population density

(Basemap: ESRI, 1999).

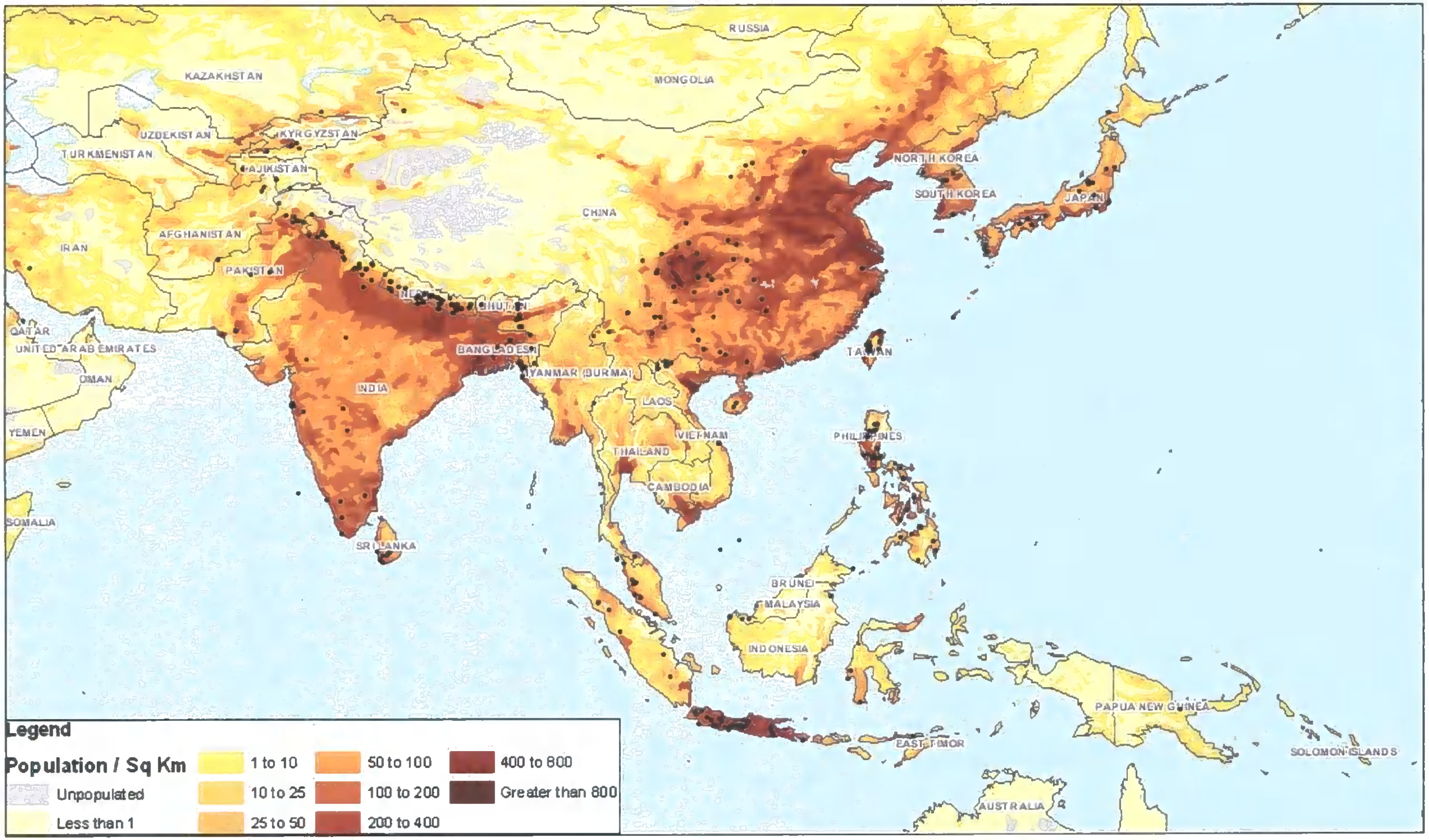


Figure 4.10 Fatal landslide events and population density in Asia

(Basemap: ESRI, 1999).

many of which actually occur in sparsely populated terrain. Here the inhabitants live in hundreds of small villages along the valleys and in a number of small, rapidly growing towns (Hewitt, 1997, 2004). As the fatality map illustrates (figure 4.6) fatal landslide events occurring along the Himalayan Arc are of predominantly low magnitude (<20 fatalities), reflecting the low population densities that characterise the region. These findings suggest that the distribution of fatal landslides is not controlled by a single variable alone, for example population density, but by the interaction of several influencing factors. For example, the Karakoram is characterised by tectonically destabilised slopes and high climatic inputs making the mountain range susceptible to mass movement (Alexander, 2005). There is however, a strong correlation between high population density and fatal landslide occurrence on Java (figure 4.10). In addition, exceptionally low population densities may explain the absence of fatal landslides on the island of Papua and Papua New Guinea, which is one of the most seismically active areas on Earth and where landslide frequency is known to be relatively high (Brabb and Harrod, 1989).

A number of studies have been undertaken examining the global distribution of the human population in relation to a range of physiographic parameters, including elevation and climate (King *et al*, 1994; Cohen and Small, 1998; Small and Cohen, 1999). Small and Cohen (1999) analysed the distribution of global population relative to precipitation. They observed a normalised distribution around 800 mm of rainfall per year, areas occupied by approximately 500 million people. In addition, when analysing the annual rainfall variability over a thirty five year period, Small and Cohen (1999) observed a peak in the global population density in areas characterised by ~5000 mm of annual precipitation. This peak corresponded with the prolonged and high intensity rainfall associated with the Asian monsoon, suggesting a large number of people are vulnerable to monsoon triggered landslides (see section 4.4.3).

Examining the global distribution of population with elevation, it can be observed that average population densities diminish rapidly with increasing altitude, with inland population densities being at their highest in topographic basins adjacent to mountain ranges (Small and Cohen, 1999). Using digital elevation data from GTOPO30 and population data from the Gridded Population of the World (GPW2) produced by CIESIN (2000), Duncan (2001) analysed the spatial distribution of the global population in relation to elevation, concluding that 10% of the global population inhabited areas above 4,000 feet (1220 meters). These data provide an indication of the total number of people living in mountain environments which are highly susceptible to mass movement events.

4.2.4 Vulnerability in rural and urban areas

"Vulnerability of both megacities and small communities is determined by their physical and social exposure, disaster resilience, pre-event mitigation or preparedness, and post-event response" (Cross, 2001: 64).

Nearly half of the global population lives in urban areas and this is projected to increase to 60% by 2030 (United Nations, 1999) (figure 4.11). In addition, approximately 400 million people live in megacities, half of whom are located in seismically-active zones (Bilham, 2004). While the urban population is increasing over time, a larger percentage of the population occupies rural areas. In addition, cities cover a small fraction of the area of most countries and <1 % of the Earth's total land area (Hewitt, 1997). However, the significance of urban risk arises from the actual and potential scales of disasters occurring within cities resulting from the number of people concentrated in a defined and limited space (Alexander, 1989; Anderson, 1992; Steedman, 1995; Hewitt, 1997; Smyth and Royle, 2000; Cross, 2001). With this in mind, it has suggested that the impact of fatal landslides is greater in urban than in rural areas (Alexander, 2005).

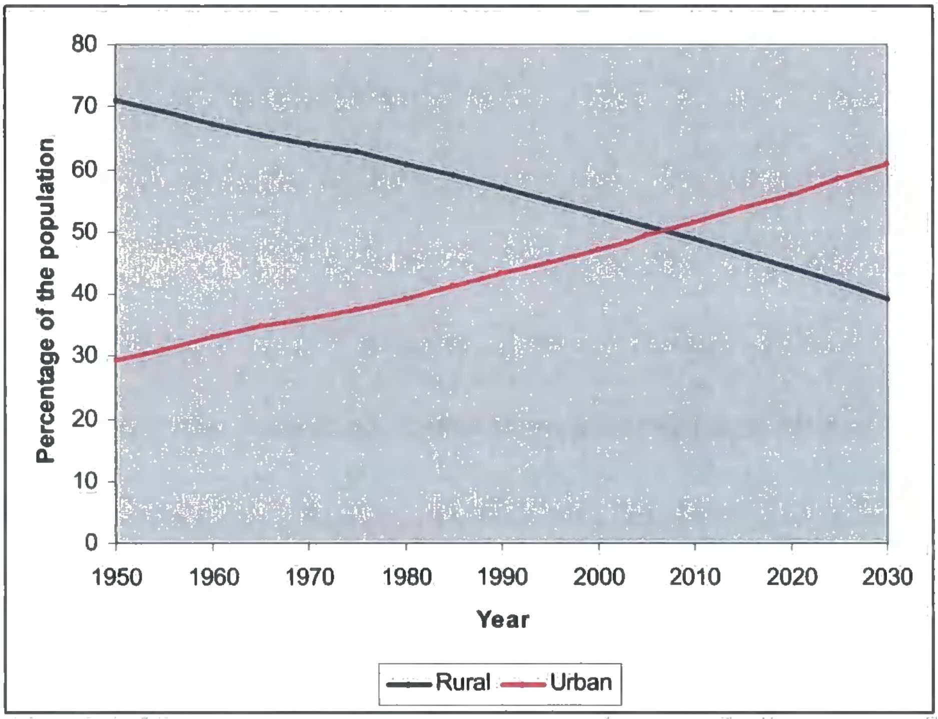


Figure 4.11 The percentage of the world population living in rural and urban area (The United Nations Population Division, 2004).

The occurrence of landslides in terms of rural/urban setting has been analysed with difficulty because the data on the actual setting of the landslide is poor or in some cases missing and multiple events may affect both urban and rural areas. Thus, only events where the location is known with confidence are included. In addition, it has been recognised that the number of fatal landslide events is underreported for rural areas (section 2.2). The figures citied here are therefore likely to underestimate the impact of landslide hazard events. For the fatal landslide events recorded within the landslide database, the frequency of occurrence was far greater in rural than in urban areas, with 74% of events occurring in hamlets, villages and other sparsely settled areas. While only 26% of the landslide events recorded occurred in urban areas, these events accounted for 59% of the total fatalities.

Assessing the occurrence of fatal landslides within rural areas

Rural landslides were found to be relatively low in magnitude, characterised by an average of 19 fatalities per event. These included rock falls striking cars travelling along mountain roads, landslides burying houses and communities, and landslides generated by engineering or mining activities. In total, 41% of the recorded fatalities occurred within rural areas.

The lower fatality totals observed may be explained by the relatively low population densities that characterise rural areas. However, rural areas are not necessarily sparsely populated. For example, rural population densities in parts of east and south Asia often exceed that of many American suburbs (Cross, 2001). In addition, while rural areas and small urban centres may have smaller total populations, often a far higher proportion of their population is vulnerable to hazard events (Degg, 1992; Cross, 2001; Bull-Kamanga *et al*, 2003). These areas are susceptible to a different set of vulnerabilities, which stem from neglect, repression and deprivation of the poor (Alexander, 1993). While there is undoubtedly poverty and inequality within most cities that gives rise to spatial variations in vulnerability, in comparison with rural areas large urban centres often have greater financial capabilities and expertise to mitigate against disasters and to deal with the aftermath (Cross, 2001). In addition, the focus of the International Decade of Natural Disaster Reduction was risk reduction within megacities (Steedman, 1995; Mitchell, 1999). Thus the urban environment was and continues to be the focus of disaster management strategies and associated investment.

Loss of life from landslides is related to the speed of onset/movement and the state of immediate awareness of the event among potential victims (Alexander, 1989). With this in mind a possible explanation for the higher frequency of fatal landslide events may be related to the comparative absence of risk assessments, slope monitoring and mitigation being undertaken within rural areas.

While the high frequency, localised events were characteristically low in magnitude, the impact of high magnitude, multiple mass movement events is often felt more heavily in outlying communities than in urban areas (Cross, 2001). Examples include the 1999 Venezuelan mudslides, which not only caused destruction within the urban centre of Caracas where ~40 people were killed, but also caused devastation throughout eight states including the rural areas in Miranda and Vargas, resulting in ~40,000 fatalities (Ministry of Planning and Development, 2000). Debris flows triggered by the volcanic flank collapse of Casita volcano in Nicaragua in 1998 were also seen to destroy several towns and smaller settlements causing ~1680 fatalities (author's dataset).

Assessing the occurrence of fatal landslide events within urban areas

Fatality totals in urban areas ranged from 1 to >3,000 fatalities, with an average of 77 deaths per landslide event (58 more fatalities per event than in rural areas). Indeed as noted by Hewitt (1997), while a smaller fraction of fatal landslide events occur in cities they are generally more lethal when they do occur and are often associated with extensive devastation and high numbers of casualties. This pattern is certainly evident within the database.

However, when considering the occurrence and impact of fatal landslide events within urban areas, the focus is often placed on shanty-style settlements, precariously balanced on hill slopes in rapidly expanding third world cities. Certainly, a disproportionate share of megacities are located in less developed countries where poverty, political and social inequalities combine to heighten the vulnerability of the urban population (Cross, 2001; Cannon, 1994; Wisner *et al*, 1994). The growth of urban areas has resulted in the physical expansion of cities with the occupation of sites at high risk from disasters, including hillsides, slopes and other land subject to instability (Jimenez Díaz, 1992; Smyth and Royle, 2000; Bull-Kamanga *et al*, 2003).

Having analysed the location of the 744 fatal landslide events recorded within the landslide inventory, only 14 of the events are associated with urban slums and shanty-style settlements. Examples include the 1999 floods and mudslides in Venezuela in the densely populated hillside suburbs of Caracas; an earthquake induced landslide which buried a shanty-town on the outskirts of San Salvador killing ~518 people and the 1999 landslides in Manila in the Philippines, which buried 300 houses killing ~59 people. In total the 14 events caused ~1,000 fatalities (2% of the total number of fatalities recorded). This is surprising given the commonly held perception that people living in shanty-style settlements are a highly, if not the most, vulnerable group of people to landslide events. This misrepresentation may be attributed to media sensationalism which focuses on larger magnitude events and pays comparatively little attention to rural disaster losses which are less concentrated, less dramatic and seemingly less significant (Lewis, 1984).

Alternatively, the relatively low fatality totals associated with shanty-style settlements may reflect better management of the urban environment. For example, Chau *et al* (2004) analysed the spatial distribution of landslide events within Hong Kong between 1984 and 1996, where 28% of landslides were seen to affect squatter settlements. However, with their gradual decrease following the implementation of effective public housing policy, shanty-style settlements are becoming increasingly less vulnerable to landslide events. Similar schemes include the Favela Bairro squatter settlement upgrading programme in Rio de Janeiro, Brazil (Riley *et al*, 2001). Such programmes, along with a better understanding of landslide causative factors and vulnerabilities, have perhaps led to the more successful management of the urban landslide problem.

Fatal landslides affecting shanty-settlements would undoubtedly reflect badly on governments and authorities who may be criticised for their lack of intervention, ineffective housing policies and the absence of building regulations. An alternative viewpoint therefore, is that not all fatal mass movement events affecting squatter settlements were/are reported. This may explain the low number of landslide events associated with shanty-settlements recorded within the database.

Undeniably, a smaller number of fatal landslide events occur within urban than rural areas. This is probably because cities have the financial capabilities and expertise to manage and mitigate against landslide disasters. Examples include the densely settled urban areas of Hong Kong island and the Kowloon Peninsula which are highly susceptible to landsliding (Chen and Lee, 2004). A number of fatal landslides have historically occurred (Premchitt *et al*, 1994; Chau *et al*, 2004) including the 1972 Sau Mau Ping landslide in eastern Kowloon which destroyed a housing estate killing 71 people, and the Po Shan Road landslide on the same day which destroyed two apartment blocks resulting in 67 deaths on Hong Kong Island (GCO, 1972).

Hong Kong is highly susceptible to landsliding due its characteristic hilly terrain and intense rainfall, which triggered 90% of recorded slope failures (Chen and Lee, 2004). Undoubtedly, landsliding in Hong Kong will always occur due to its geographical setting and the geological conditions. However, despite rapid urbanisation within difficult terrain, the number of fatal landslides recorded has rapidly decreased. Indeed, analysing the landslide database it can be concluded that no fatal landslides have been recorded for Hong Kong since 1994. This has been largely associated with the implementation of Hong Kong's landslide prevention strategy and long-term public safety programme in 1977 which involves regular maintenance of slopes (for example, constructing retaining walls, anchoring slopes, implementing effective drainage systems and revising slope geometry) (Chen and Lee, 2004; Malone, 2005).

4.2.5 The impact of landuse change

Slope failure has also been viewed as the product of contemporary land use change occurring in association with a physical trigger (Smyth and Royle, 2000). This model is relevant to both the urban and rural environment as examples of activities resulting in land use change include road construction, deforestation, terracing and changes in agricultural practices (Barnard *et al*, 2001), activities often linked to rising population pressures (Gerrard and Gardner, 1999).

Road construction in rural mountain environments is often associated with landslide activity (Owen, 1996; Sarkar, 1999; Pascual, 2001; Chang and Slaymaker, 2002; Pande *et al*, 2002; Barnard *et al*, 2001). However, only four landslide events recorded within the inventory were directly associated with road construction, resulting in a total of 45 fatalities (0.08% of the total deaths recorded). This is surprising given the high frequency of fatal landslide events recorded for the Himalaya and the problems associated with road construction within the region (Pascual, 2001).

Rising population pressures, poverty and third world debt burdens are believed to be increasing the pressures placed on forest resources. Extensive deforestation has occurred increasing the level of soil erosion, the impact of high intensity rainfall events and subsequent landslide activity (see '*The Theory of Environmental* Degradation' in Ives, 2004, pp.4-5). However, deforestation was associated with only five fatal landslide events in the database. These occurred in Indonesia (266 fatalities), the Philippines (154 fatalities) and the USA (18 fatalities) and accounted for ~1% of recorded fatalities. These findings are surprising given the common link that is often made between landslide occurrence and deforestation. However, Ives and Messerli (1989) and Ives (2004), with reference to the Himalaya, have rejected claims that widespread deforestation has been occurring. Instead, while it is suggested that some forests have been subject to clearance, environmental reports have often been deliberately distorted. Perhaps therefore, the relationship between deforestation and landsliding has been heightened by sensationalised media representations that focus on and magnify the human mismanagement of the environment.

It has sometimes been suggested that landsliding is based on a cycle, with large scale landslide events being followed by periods of inactivity (Carson, 1985 cited in Ives, 2004). Thus, periods of relative stability are required to enable the accumulation of newly weathered mantle in preparation for the next major failure (Ives, 2004). Forested slopes merely postpone the occurrence of a cycle and instead facilitate the production of a deeper debris mantle that subsequently results in large scale events with longer recurrence intervals. While deforested slopes may be destabilised more frequently, these tend to be small, shallow failures. This may explain the low number of fatal landslide events associated with deforested slopes recorded within the landslide database. Alternatively, a far more likely explanation is that deforestation (and road construction) are causative or predisposing factors that increase the susceptibility of slopes to failure rather than actually triggering movement. As a result, their role is unlikely to be evident within the database.

A number of studies have been undertaken examining the impact of agricultural practices on landslide occurrence. Examples include the work of Gerrard and Gardner (1999, 2000a, 2000b and 2002) who analysed the nature, cause and incidence of landsliding on steeply farmed slopes in the Middle Mountains of Nepal. They concluded that while landslides do occur on rain-fed and irrigated terraces they tend to be small, easily repaired local slippages. While large mass movement events do occur, they are rarely generated under normal monsoon conditions and are largely unrelated to farming activities, although there are exceptions where failures occurr on abandoned agricultural terraces (Gerrard and Gardner, 2002).

While it is commonly assumed that landsliding is the direct consequence of human land-use and land-cover changes over recent decades (Ives, 2004), the findings presented above suggest otherwise and may explain the absence of such events within the landslide database. However, as previously noted, the majority of landslide events recorded within the database were associated with a physical trigger, making it difficult to empirically assess the impact of human activity and to preclude any quantification of its influence.

4.2.6 Summary

Mitchell (1999) examined megacities and natural disasters and noted that at *"the global scale, large natural disasters are popularly associated with rural populations and poor countries"* (pp.137). Mitchell (1999) went on to challenge this assumption and argued that cities and more specifically megacities were becoming the major arenas for natural disasters, a view that has dominated current thinking since the International Decade of Natural Disaster Reduction. However, the findings from this study suggest that globally, fatal landslide events predominantly occur in middle income countries and within rural areas. Along with the work of Cross (2001), who examined hazard vulnerability in megacities and small towns, these findings challenge the assumption that urban areas and in particular megacities are ***uniquely*** and ***excessively*** vulnerable to fatal landslide events.

As hypothesised, the number of recorded deaths was lowest in high income countries. To a degree this may be locationally driven (Alcántara-Ayala, 2002) with high income countries being largely located outside the monsoon, typhoon and earthquake zones. High income countries are also seen to have the financial capabilities and expertise to mitigate against landslide disasters. Hence, while more events were recorded for high, rather than upper middle income countries, the impact in terms of fatalities was lower. Despite these findings, the overall occurrence of landslide fatalities did not correlate with levels of economic development, with the highest numbers of fatalities occurring within middle rather than low income countries.

Issues and patterns of vulnerability are undoubtedly very different between urban and rural areas. However, it would seem that rural communities are more vulnerable to landslide events than urban populations despite lower population densities, reflecting the larger spatial extent of rural areas. In terms of the impact of landslide events, the highest numbers of fatalities were associated with urban landslides, a finding that can be attributed to the high number of people and activities concentrated in a defined and limited space (Anderson, 1992).

An attempt was also made to assess the impact of severe land degradation on the occurrence of fatal landslide events. The above commentary suggests that despite anecdotal evidence to the contrary, few fatal landslide events were associated with deforestation, road construction and agricultural land-use change. However, while the impact of human land-use change may be overplayed, it is not possible to preclude its influence as little is known about the site specific pre-landslide activities giving rise to slope failure.

4.3 ANALYSING THE SPATIAL DISTRIBUTION OF FATAL LANDSLIDE EVENTS: THE PHYSICAL PERSPECTIVE

4.3.1 Introduction

Extensive research has been undertaken examining the relationship between landslide occurrence and geo-environmental factors including geomorphology, lithology, climate and land cover (Varnes, 1978; Caine and Mool, 1982; Cruden, 1993; Bookhagen *et* al, 2001; Zhou *et al*, 2002; Gerrard, 2000, 2002; Gabet, 2004). A range of physical triggers of landslide activity have subsequently been identified including intense, prolonged rainfall, snowmelt, seismic shaking, volcanic eruption, stream erosion and natural dam failure (Schuster and Wieczorek, 2002).

A fundamental way of analysing the relationship between landslides and their causative factors is to examine the distribution of landslide events in relation to a range of physical factors (Carrara *et al*, 2002). A series of datasets including mean annual global precipitation and global relative relief have been gathered and the relationship between the distribution of fatal landslide events and the above variables analysed using ArcGIS.

4.3.2 Data Sources

Mean annual precipitation

Rainfall is reported to be the most frequent landslide generating mechanism (Alexander, 2005; Benn, 2005) and this is confirmed by the database. However, the key question is whether the landslide triggering factor is rainfall amount or rainfall intensity. The landslide database highlights the importance of high intensity precipitation often associated with the annual monsoon and tropical cyclone events, suggesting rainfall intensity to be the key parameter. This builds upon the findings of Dhakal and Sidle (2004) who investigated the impact of different rainfall conditions on slope stability. They observed that the combined influence of mean and maximum hourly intensity, duration, and total rainfall amount of rainstorms were important in generating landslides. However, while a number of localised studies also highlight the importance of rainfall intensity (Zhou *et* al, 2002), others suggest rainfall duration to be the most important triggering factor (Hardenbicker *et al*, 2001) along with the antecedent conditions (Jakob and Weatherly, 2003). The impact of rainfall will depend upon a number of landslide conditioning factors including lithology and geological structure, slope angle and slope morphology, land use, the presence of old landslides, and human activity (Zezere *et al*, 1999). This makes the relationships between landsliding and rainfall amounts/intensity highly complex (Garrard and Gardner, 2000).

While a number of localised, small scale studies have examined the impact of rainfall intensity on landslide occurrence (Ng and Shi, 1998; Luino, 2005), such data sets are not available at the global scale. The distribution of events has therefore been analysed in relation to global precipitation patterns. These data were provided by Duncan (*pers comm*) and sourced from Willmott and Matsura of the Centre for Climatic Research, University of Delaware. The raw (rain gauge-measured) monthly precipitation data were sourced from Global Historical Climatology Network version 2 (based upon readings from 20,599 stations) and Legates and Willmott (1998) (based upon readings from 26,858 stations), providing coverage from 1950 to 1999. Willmott and Matsura performed a climaticallyaided interpolation to put the data onto a 0.5° grid (~50 km at the equator). The data used here were the mean annual values, provided in the form of an ArcGIS raster grid.

The limitations of using mean annual rainfall totals rather than a rainfall intensity dataset are recognised, however this analysis does develop our understanding of the relationship between landslide occurrence and the rainfall variable on a global scale.

Global relative relief

It has long been acknowledged that relief is more important than altitude in influencing the occurrence of erosional events such as landslides (Ahnert, 1970; Hewitt, 1972; Schumm, 1977; Phillips, 1990). With this in mind the distribution of fatal landslide events has been analysed in relation to global relative relief. These data were provided by Duncan (*pers comm.*) and sourced from SRTM30 which is a digital elevation dataset generated by NASA and the National Imagery Mapping Agency as part of the Shuttle Radar Topography Mission. SRTM30 updates earlier global digital elevation models including GTOPO5 and GTOPO30 providing high resolution, global coverage at 30 arc-seconds (~1 km at the equator) (SRTM30 Data Information, 2005). A relief grid was created from this dataset by Duncan based upon a simple maximum elevation difference between each cell and its eight neighbours. These relief values were then averaged over 5 x 5 cell blocks to obtain the mean kilometre-scale relief at 2.5 km resolution. An ArcGIS raster map of relative relief was subsequently generated.

Combined relative relief and precipitation (an erosion index)

As before, these data were provided by Duncan (*pers comm*) in the form of an ArcGIS raster map. Values from the mean annual precipitation and relative relief grids were multiplied together on a cell-by-cell basis at the 2.5 km resolution using ArcView Spatial Analyst (software designed to create, query, map and analyse cell-based raster data), creating an erosion index (Duncan, *pers comm.*). It is important to note that the precipitation and relative relief datasets were at very different resolutions (~50 km and ~2.5 km respectively); therefore, within each 0.5° grid cell all calculated relief values were associated with the same mean annual precipitation totals.

All datasets were available in the standard global coordinate system of latitude and longitude on the WGS84 datum.

4.3.3 Data analysis

Figures 4.12, 4.14 and 4.16 illustrate the spatial relationship between fatal landslide occurrence, mean annual precipitation, relative relief and a global erosion index. In addition, to enable more rigorous analysis to be undertaken, detailed regional maps were also generated using ArcGIS. These focused on Asia where the majority of fatal landslide events were recorded (figures 4.13, 4.15 and 4.17).

Figure 4.12 illustrates the spatial distribution of fatal landslide events in relation to mean annual precipitation. The majority of fatal landslides occurred in areas characterised by high annual precipitation including South East Asia, the Himalaya and Central

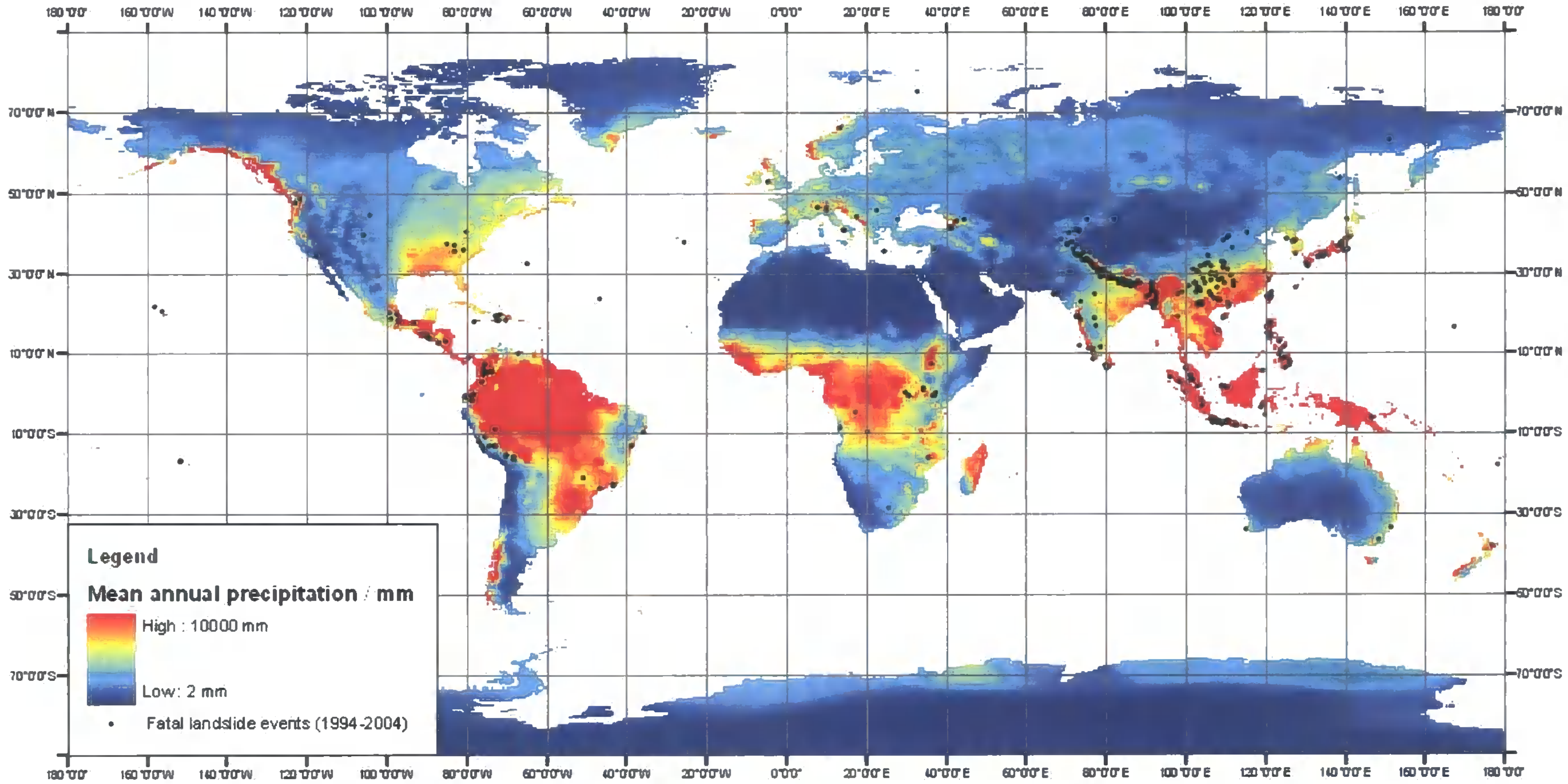


Figure 4.12 The spatial distribution of fatal landslide events in relation to global mean annual precipitation totals.

(Source: Rainfall data derived from Willmott *et al*, 1998 and created into a raster image by Duncan, *pers comm*).

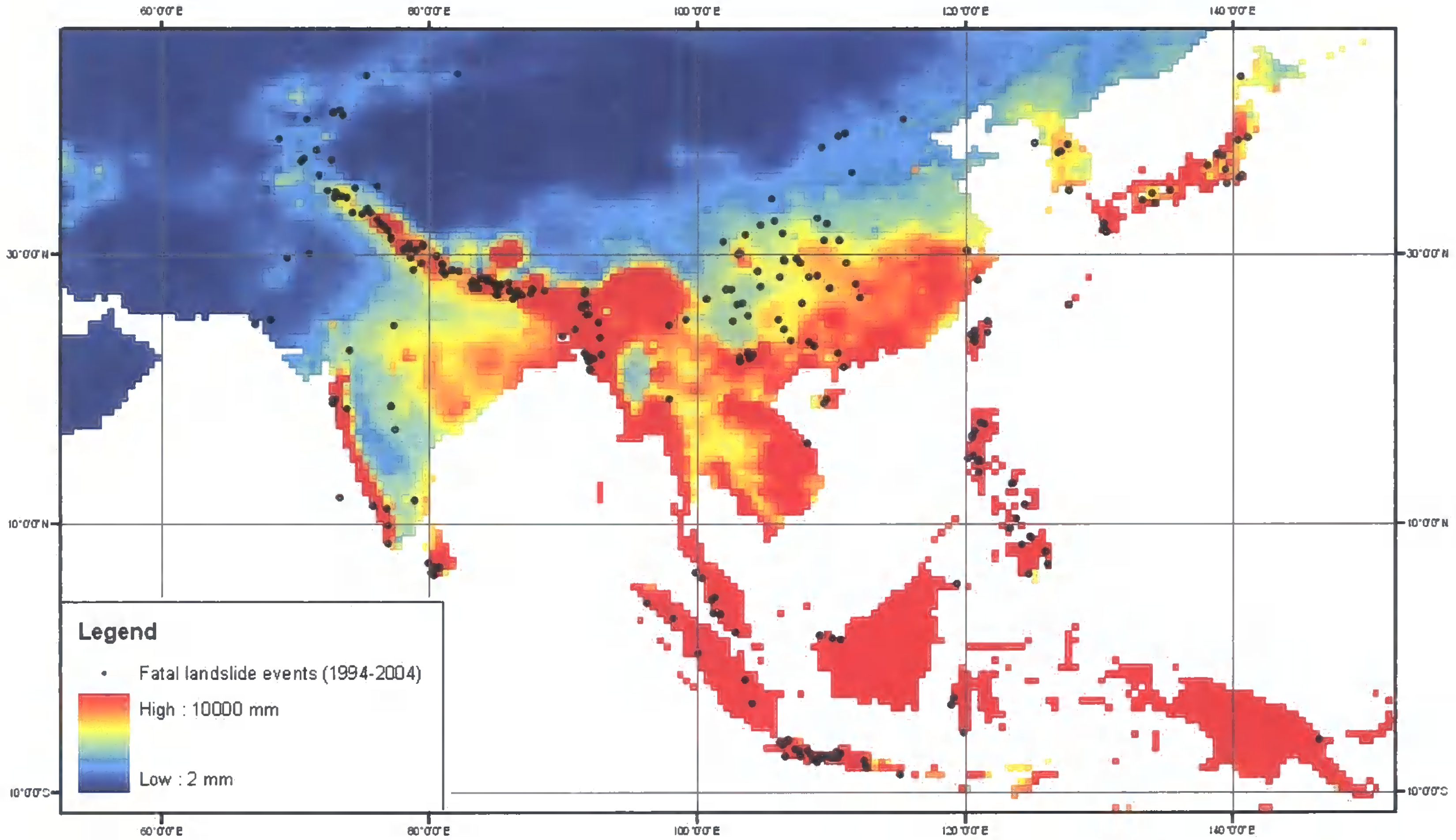


Figure 4.13 The spatial distribution of fatal landslide events in Asia in relation to mean annual precipitation.

(Source: Rainfall data derived from Wilmott *et al*, (1998) and created into a raster image by Duncan, (2005)).

America. These findings suggest a strong positive correlation between high annual rainfall and fatal landslide activity. Focusing specifically upon Asia (figure 4.13), landslides clustered in areas receiving high annual rainfall totals in western and northern India, Nepal and Bhutan (areas affected by the South Asian monsoon), Southern China (affected by the East-Asian monsoon), Malaysia and Indonesia (countries affected by seasonal rainfall), the Philippines, Taiwan and Japan (affected by the Northwest Pacific Tropical cyclone season). Outside Asia, fatal landslides were also seen to occur in areas receiving exceptionally low annual rainfall totals, for example the USA, Middle East, Kyrgyzstan, Pakistan and central/northern China. These events may also have been triggered by rainfall, as the threshold for rainfall induced failure depends upon a number of factors including geology, porosity and slope angle (Burbank and Anderson, 2001). Alternatively, the observed spatial distribution of fatal landslide events may be explained by other landslide triggering mechanisms, for example seismic shaking.

Figures 4.14 and 4.15 illustrate the spatial distribution of fatal landslide events in relation to mean relative relief. Landslides occurred in areas characterised by high relative relief for example, western Canada and western USA (areas associated with the Pacific Mountain system and the Rocky mountains), the Andes mountain chain along the western coast of South America, the Alps in central Europe, the Himalaya and the moderate mountain ranges of southern China. Focusing specifically upon Asia, the landslides cluster from Kyrgyzstan along the Himalayan arc through India, Pakistan, Nepal, Bhutan to southwest China and Taiwan. As noted by Brunsden and Allison (1986) high mountain environments are often associated with violent, high magnitude processes due to their scale,

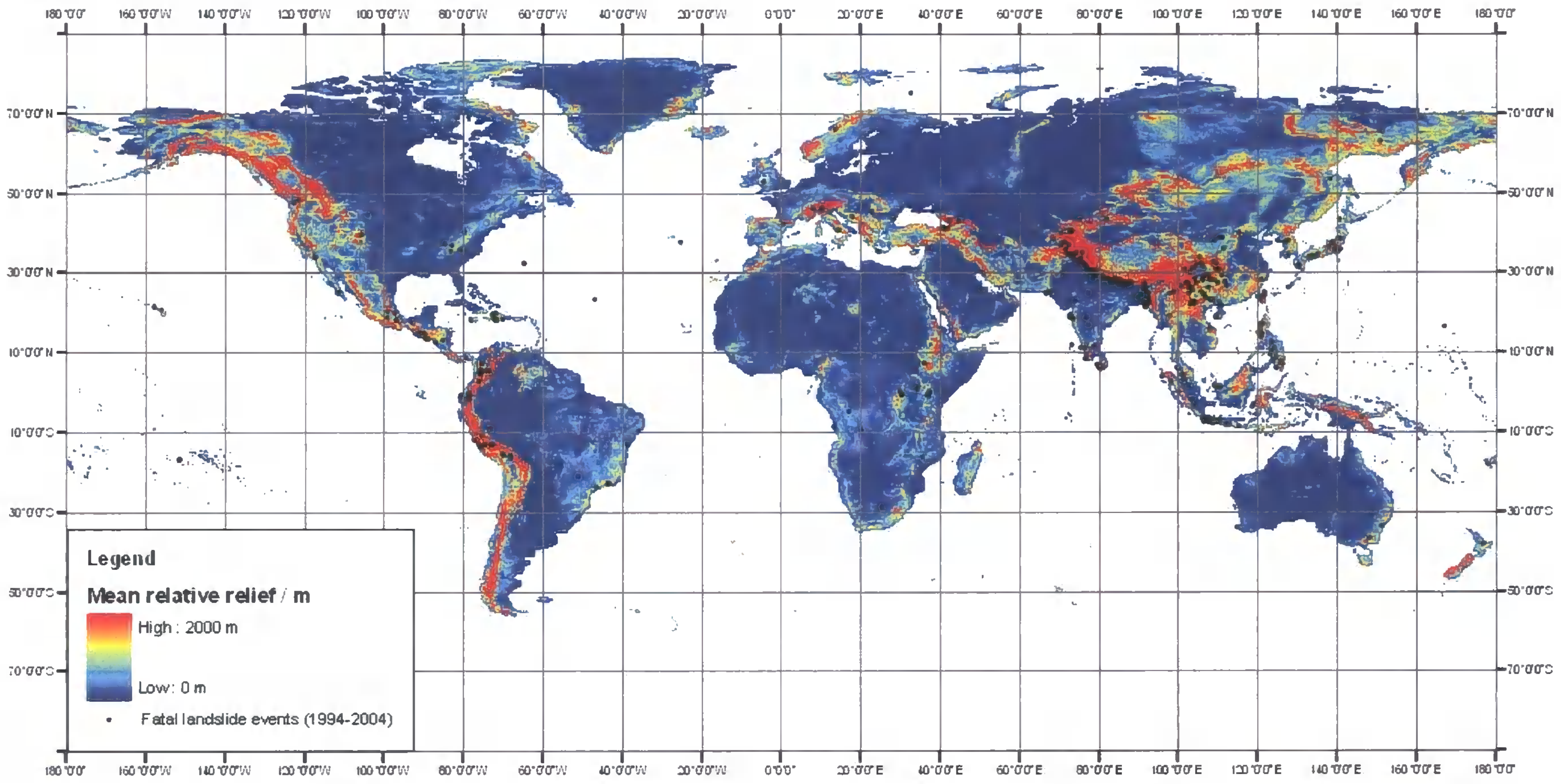


Figure 4.14 The spatial distribution of fatal landslide events in relation to global mean relative relief.

(Source: Relief data derived from SRTM30 provided and created into a raster image by Duncan, *pers comm*).

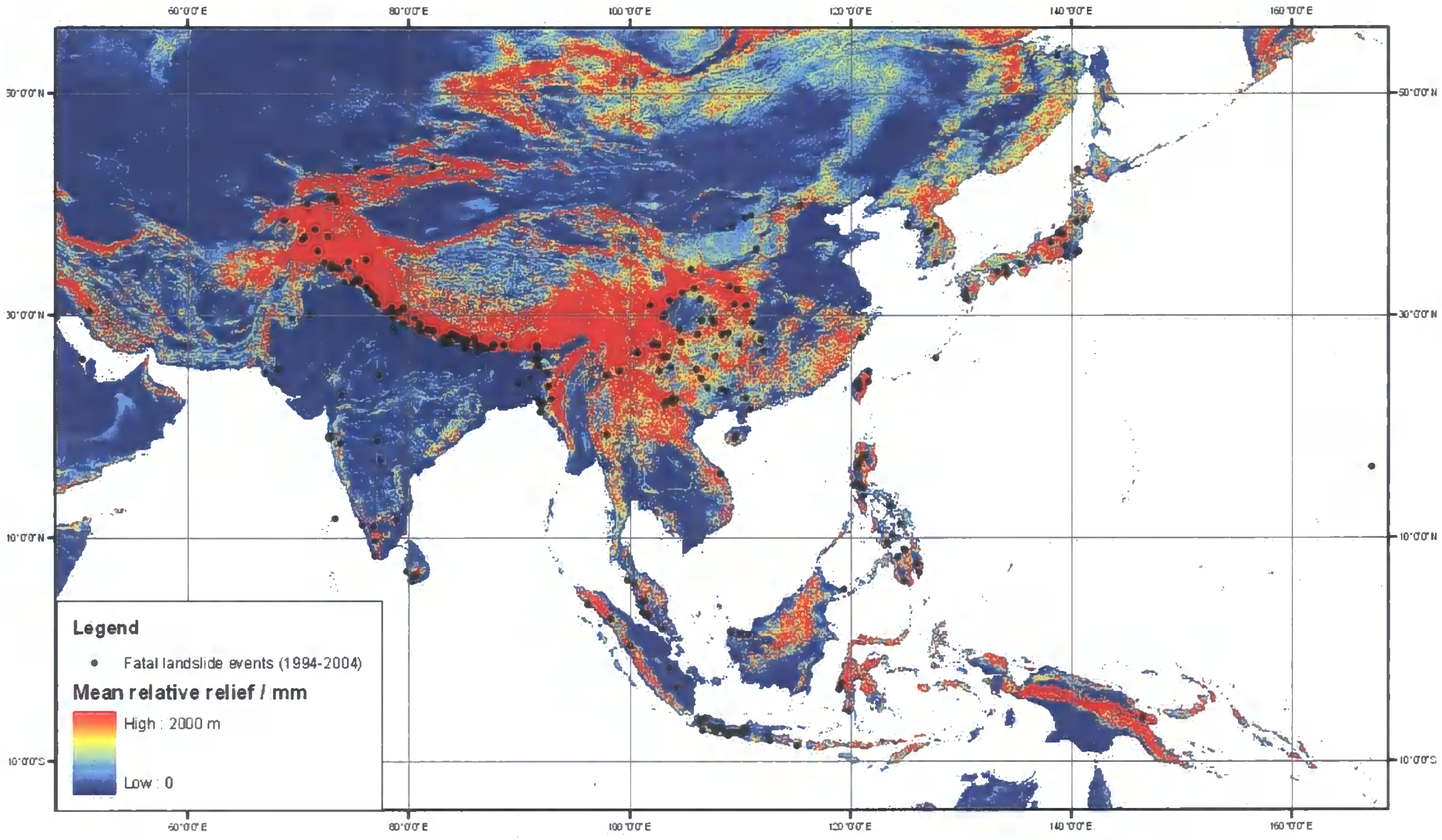


Figure 4.15 The spatial distribution of fatal landslide events in Asia in relation to relative relief.

(Source: Relief data derived from SRTM30 provided and created into a raster image by Duncan, 2005).

steepness of slope and unstable material often resulting from rapid tectonic uplift and fluvial and glacial incision (Barnard *et al*, 2001). Mass movements are seen to occur regularly in areas of high relative relief forming part of the landscape development process (Scheidegger and Ajakaive, 1994). Some fatal mass movement events also occurred in areas characterised by low relative relief. However, while the relief may be relatively low, little is known about the slope morphometry and in particular, the slope angle characteristics or the geology/lithology of the landslide sites, factors often cited as the predominant controls on slope failure (Shroder and Bishop, 2004).

Figures 4.16 and 4.17 examine the relationship between both the precipitation and relative relief variables in the form of an erosion index and fatal landslide occurrence. The observed pattern was as expected; areas of high relative relief were largely associated with high annual rainfall totals, a result of the interplay between topography and atmospheric circulation (Barry, 1992; Bookhagen *et al*, 2005; Kansakar *et al*, 2004). Landslide fatalities were largely concentrated in these areas (for example, along the Himalayan arc, the central mountain ranges of Taiwan, Barisan Mountains along western Sumatra, on the volcanic island of Java and the mountainous islands of the Philippine archipelago) findings that appear consistent with the accepted understanding that spatial variations in precipitation and slopes correlate with erosion rates (Burbank *et al*, 2003). However, a few fatal mass movement events were also seen to occur in areas characterised by low relative relief and low annual precipitation totals for example, central India. These events may have been triggered by an alternative mechanism, such as anthropogenic activity, seismic shaking and/or the failure may have occurred on a relatively steep slope in an area characterised by low relief, highlighting the potential significance of localised topographic variations

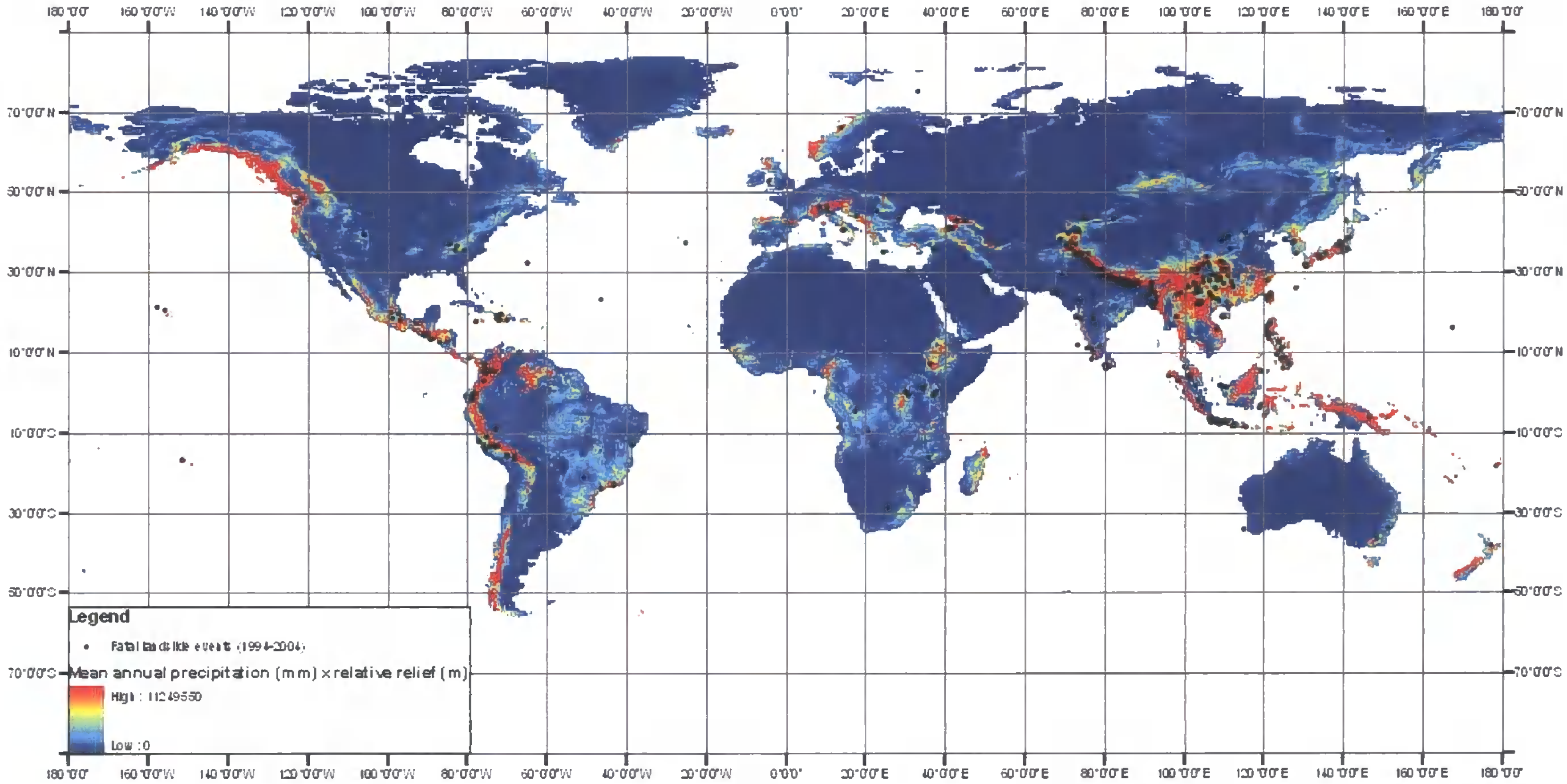


Figure 4.16 The spatial distribution of fatal landslide events in relation to mean annual precipitation and relative relief (erosion index).

(Source: Rainfall data derived from Wilmott *et al*, (1998) and relief data derived from SRTM30 created into a raster image by Duncan, *pers comm*).

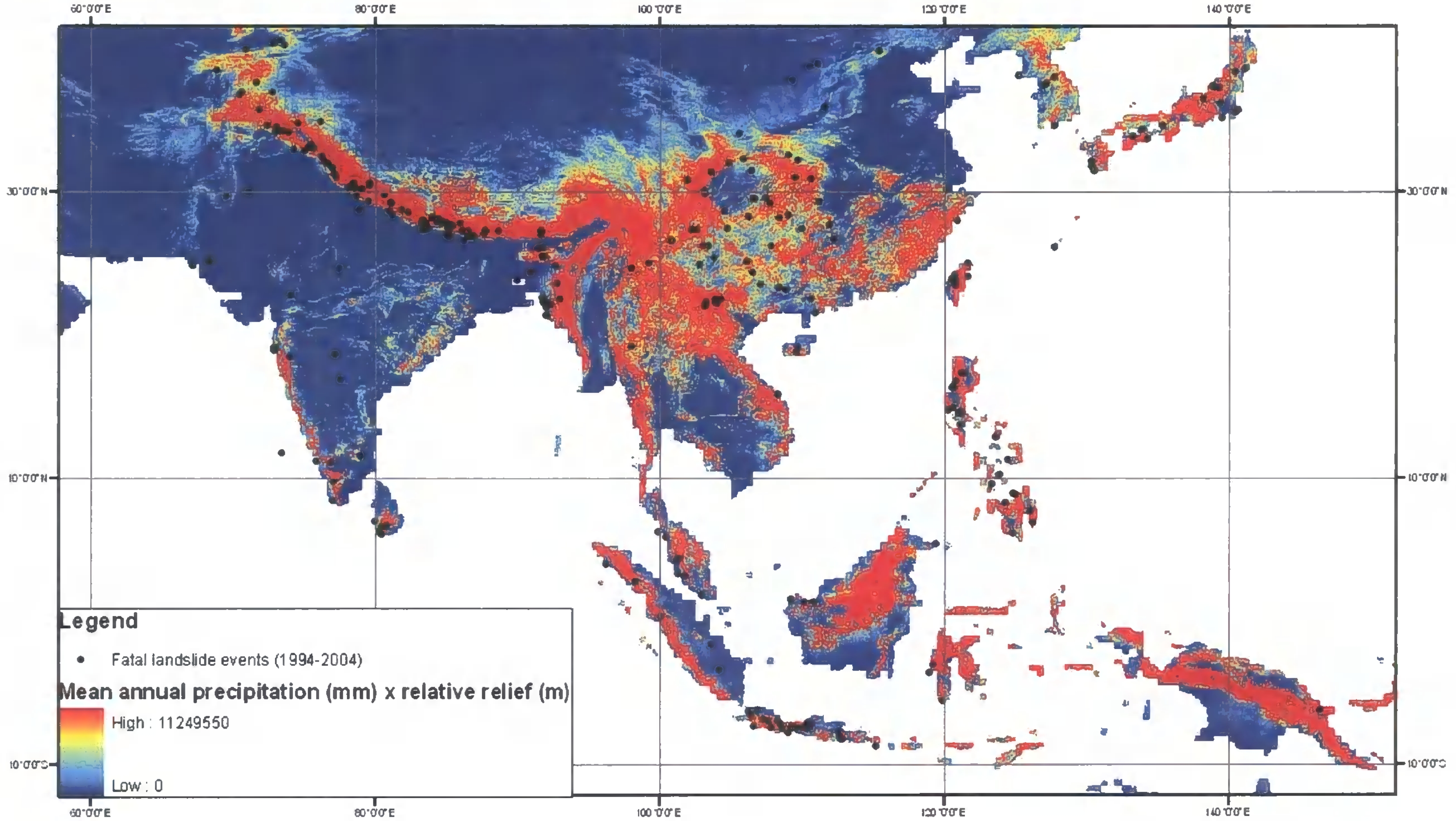


Figure 4.17 The spatial distribution of fatal landslide events in Asia in relation to mean annual precipitation x relative relief.

(Source: Rainfall data derived from Wilmott *et al*, (1998) and relief data derived from SRTM30 created into a raster image by Duncan, 2005).

With this in mind, analysing the distribution of fatal landslide events in relation to slope morphology would perhaps be more suitable than relative relief, as slope angle is one of the dominant predisposing factors influencing the occurrence of mass movement events (Moreiras, 2005; Montgomery and Brandon, 2002).

4.3.4 Denudation as an indicator of landslide activity

As previously noted, values from the mean annual precipitation and relative relief grids have been multiplied on a cell-by-cell basis to create a global erosion index (Duncan, *pers comm.*). Areas characterised by high relative relief and high annual precipitation inputs were classified as areas highly susceptible to erosion. These areas were seen to correlate with the occurrence of fatal landslide events. This is unsurprising given landsliding is a form of mass wasting and as such contributes significantly to the removal of material, often dominating the erosional processes in active mountain belts (Hovius *et al*, 2004).

Denudation refers to all weathering and erosional processes that result in the removal of material and the subsequent reduction in the elevation and relief of the land surface (Selby, 1982, Summerfield, 1994; Caine, 2004). Based upon the above findings, factors influencing denudation rates in active orgogens may provide an explanation for the global spatial distribution of fatal landslide events. This has been explored further using Taiwan as a case study, where extensive research on denudation has been undertaken including the work of Milliman and Syvitski (1992) and Hovius *et al* (2000). They report some of the highest denudation rates in the world for the Central range in Taiwan and identify landsliding as a significant process (Caine, 2004). Dadson *et al* (2003) examined links between erosion, runoff variability and seismicity in the Taiwan orogen. While the common assumption is that erosion rates are governed by relief or topography (Milliman and Syvitski, 1992), mean precipitation (Ohmori, 1983) or both (Phillips, 1990; Summerfield and Hulton, 1994; Montgomery *et al*, 2001 and Finlayson *et al*, 2002), this hypothesis does not appear to fit the modern day erosion patterns observed in Taiwan (Dadson *et al*, 2004). Instead, erosion rates on a decadal time scale were observed to be strongly influenced by large earthquakes and typhoon events. These findings are particularly relevant to this study given the time scale and have been further explored.

Earthquakes as small as magnitude 4.0 can trigger landslides on susceptible slopes, while larger earthquakes have been seen to generate thousands of landslides over vast areas, producing billions of cubic meters of loose sediment (Rodriguez *et al*, 1999). In Taiwan, Dadson *et al* (2003) observed a strong correlation between erosion rate and cumulative seismic moment release, suggesting seismic sediment production to be an important control on erosion rates. For example, the 1999 magnitude 7.7 Chi-chi earthquake triggered >20,000 mass movement events across Taiwan (Dadson *et al*, 2003).

Dadson *et al* (2003) observed a significant correlation between erosion rates and typhoon/storm activity. They concluded that storm runoff was a first order control on erosion rates in Taiwan with the events triggering primary landslides and debris flows flushing sediment from the mountain belt. These findings reaffirm those of Hovius *et al* (2000; 2004) who undertook research in the Central Range to investigate the supply and removal of sediment in a landslide dominated mountain belt. Research suggests that the majority of sediment leaving the mountain belt was generated by climate triggered mass wasting with peaks in water discharge being closely followed by peaks in sediment load transport.

Recent stream gauging records from major rivers in Taiwan have been analysed. The results imply sediment yields from the Taiwan orogen have doubled since the 1999 Chi-Chi earthquake (Hovius *et al*, 2004). However, in the first 12 months following the earthquake, erosion rates were lower than average and rates of denudation have only since risen following the remobilisation of landslide debris during subsequent typhoon events (Lin, 2005, *pers comm.*).

Based upon the above findings, the distribution of fatal landslide events has been analysed in relation to the occurrence of earthquakes and high intensity precipitation events, with a view to determining if the model proposed by Dadson *et al* (2003) for Taiwan could explain the spatial patterns and controls governing the global occurrence of fatal landslide events.

4.3.5 Analysing the spatial distribution of fatal landslide events in relation to tectonic boundaries and global seismic hazard

It is a common observation that landslide occurrence increases with proximity to tectonic structures (Saha *et al*, 2005). With this in mind the spatial distribution of fatal landslide events were analysed in relation to the position of the tectonic plate boundaries (figure 4.18). The plate boundary data was sourced from the National Geophysical Data Centre

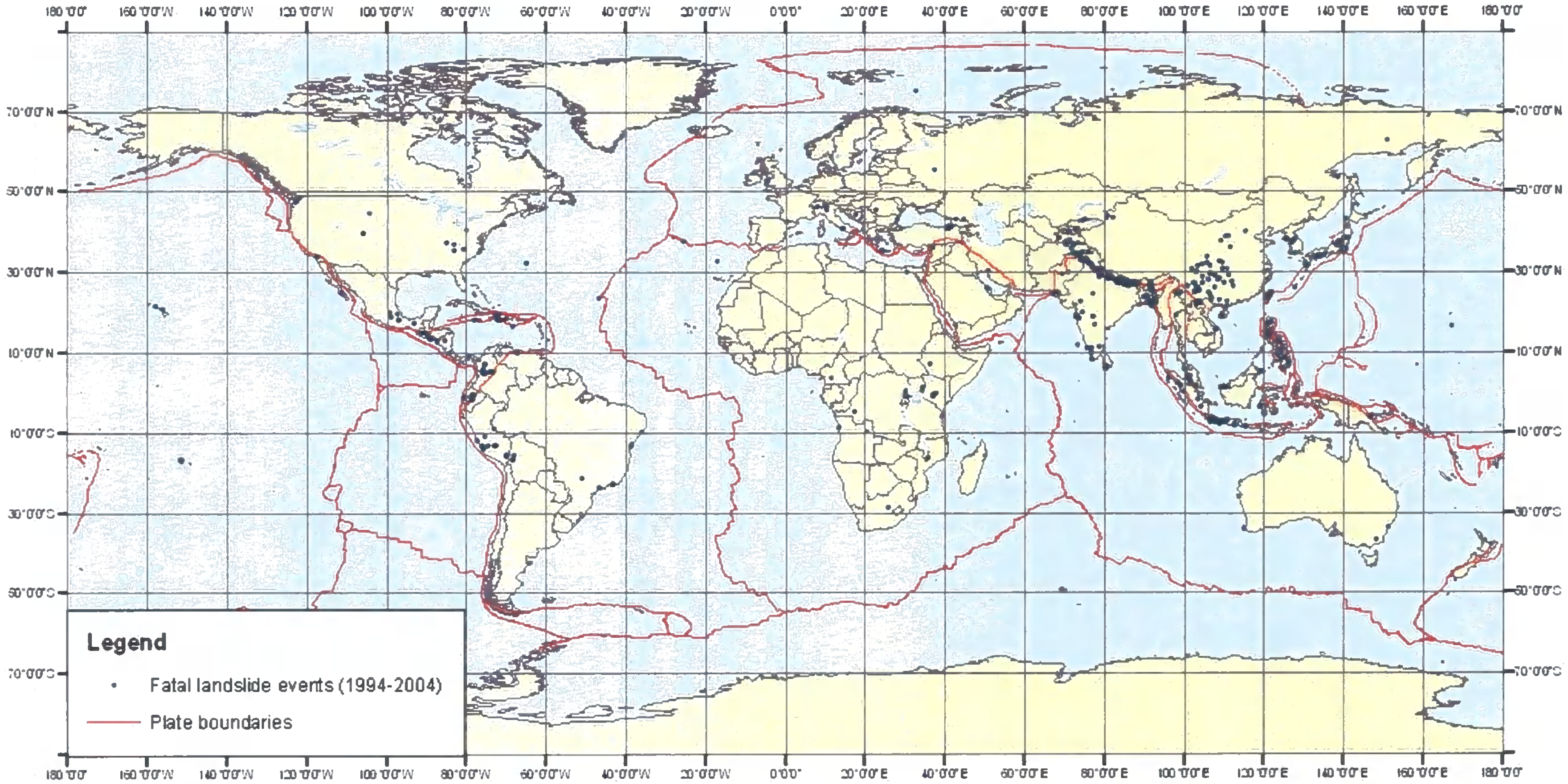


Figure 4.18 The spatial distribution of fatal landslide events (author's own data set) in relation to plate boundaries.

(Source: National Geophysical Data Centre, 2003).

and downloaded as a layer from the NGDC interactive ArcIMS natural hazard map (NGDC, 2003).

The locations of fatal landslides are seen to correlate with the outline of converging plate boundaries (figure 4.18). For example, there is a dense clustering of fatal landslides along the Himalayan Arc following the converging boundary between the Eurasian plate and the Austral-Indian plate. This clustering continues through the Indonesian archipelago, the Philippine islands and Japan. A chain of fatal mass movement events also occurred through Central America following the converging boundary between the Cocos plate and the Caribbean and North American plates. However, there was a less obvious pattern in South America along the converging boundary between the South American plate and the Nazca plate.

The initial and most obvious explanation for the observed spatial pattern is seismic activity and in order to explore this relationship further, the spatial distribution of fatal landslide events has been analysed in relation to global seismic hazard. Figure 4.19 maps the calculated peak ground acceleration (PGA) that a site can expect during the next 50 years with a 10% probability (Giardini *et al*, 1999). As expected there appears to be a strong correlation, with landslides predominantly clustered in zones of 'very high' seismic hazard (areas with an estimated PGA of >4.0 m/s^2) including the Himalayan Arc, the Andes in South America, central China, Taiwan and the Indonesian island of Sumatra. However, only 17 landslides and 2 multiple mass movement events recorded within the landslide database were triggered by earthquake events. The magnitudes of the earthquakes varied from M 4.9 to M 7.6; and the scale of impact varied from one fatality from an earthquake

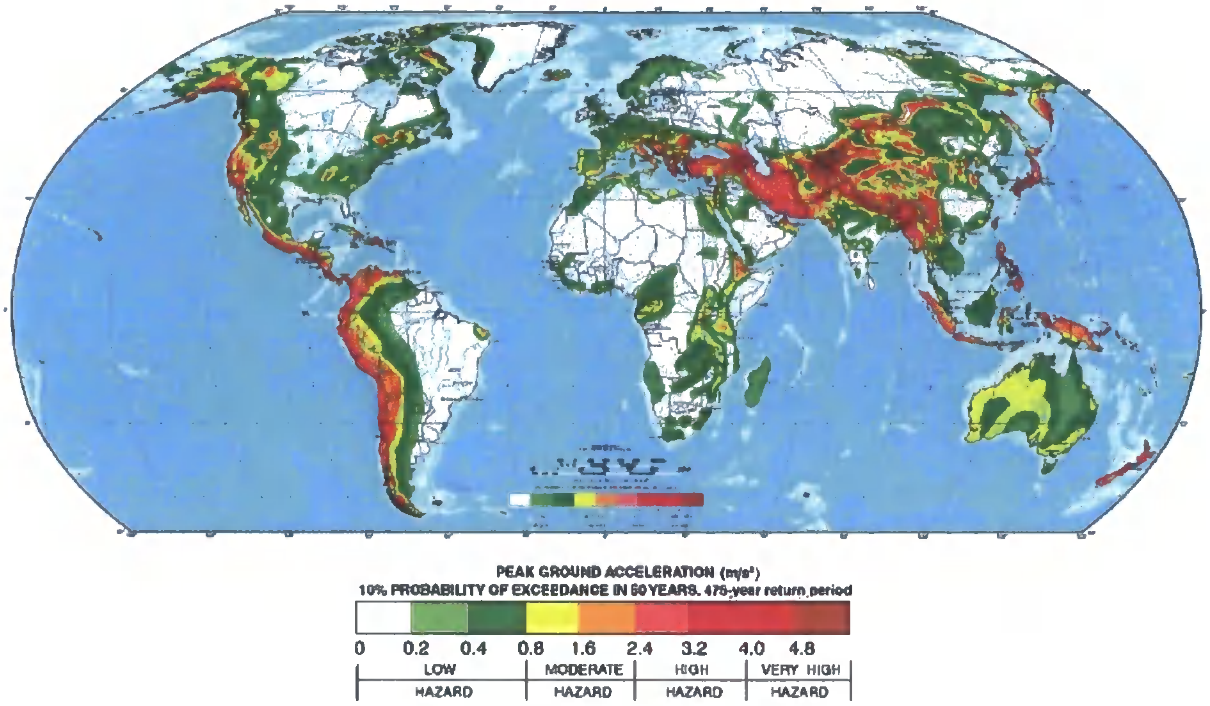


Figure 4.19 A map of global seismic hazard (Giardini *et al*, 1999).

triggered landslide in Indonesia, to 1109 deaths that resulted from earthquake triggered debris and mudflows in Venezuela. In total, earthquake triggered landslides resulted in 2,130 deaths, accounting for only 4% of the recorded fatalities within the landslide inventory. Unlike the findings of Dadson *et al* (2004) in Taiwan, the global landslide fatality data suggests that the distribution of mass movement events along converging plate boundaries is associated more with relief and orogenesis than earthquake activity.

These findings were unexpected given earthquakes as small as magnitude 4.0 have been known to trigger landslides on susceptible slopes (Rodriguez *et al*, 1999). The alternative view is that while an earthquake may not trigger slope failure, the seismic shaking associated with the event will reduce the shear strength of the slope material increasing the susceptibility of the slope to subsequent failure (Wieczorek, 1997). The occurrence of heavy rainfall following the earthquake event may therefore be enough to initiate failure, as the point of critical displacement is reached. Seismic shaking can perhaps be viewed more as a precursory trigger rather than a direct trigger of slope failure.

4.4 TEMPORAL ANALYSIS

4.4.1 Introduction

87% of the landslide events recorded within the database were triggered by high intensity or prolonged precipitation that was often associated with large scale weather systems including tropical cyclones and the annual monsoon. These rainfall induced landslides caused 94% of the recorded fatalities. It should be noted that the figures cited are likely to be an underestimation, with the trigger for many early entries within the landslide database being unknown.

An attempt has been made to use detailed annual weather reports (including the National Oceanic and Atmospheric Administration and the National Climatic Data Centre Annual Reports of Global Climate) to complete the database. These reports provide a record of significant global climatic anomalies; for example, the occurrence of tropical cyclones that triggered flooding and other associated hazards; a detailed record of the annual El Niño conditions and a summary of irregularities in the pattern of global precipitation. While the reports have proved a useful information source, they are only available from 1998. Data and information held within the landslide database between 1994 and 1997 provides a far less comprehensive picture of global landslide occurrence. With this in mind the following analyses have been undertaken:

1. **Examining the annual variations in fatal landslide occurrence**

   This analysis focused on 2003 and 2004 data which provides the most comprehensive and complete record of fatal landslide occurrence on a global scale.

2. **Examining the long term temporal trends** (analysing the 11 year subset)

   For the purposes of this analysis the dataset has been clipped to exclude events resulting in <10 fatalities and >1,500 fatalities.

4.4.2 Examining the annual variations in fatal landslide occurrence

Petley *et al* (2005) analysed the temporal occurrence of fatal landslides in 2003. They noted a bimodal distribution in the occurrence of fatal landslide events, with a concentration of events in May, June and July, followed by a second peak in November and December. The ILC database has since been updated and figure 4.20 shows the revised summary statistics where the same bimodal distribution can be seen.

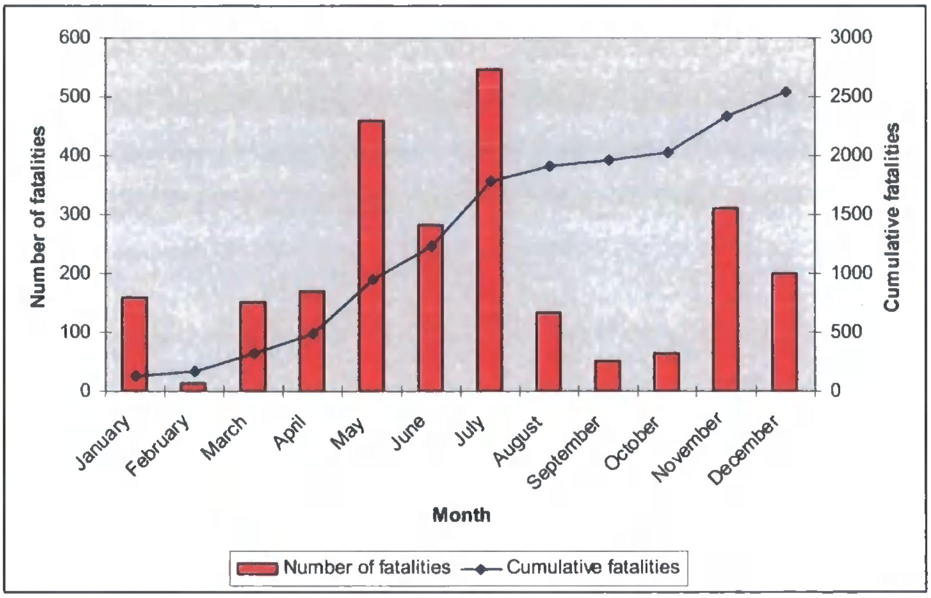


Figure 4.20 The temporal occurrence of landslide fatalities in 2003 based upon the landslide database.

Spatially, the majority of landslide fatalities occurred in Asia (figure 4.21), accounting for 82% of recorded deaths. 57% of these fatalities occurred during the northern hemisphere summer months of May, June and July and 23% during the southern hemisphere summer months of November and December. Petley *et al* (2005) attributed this pattern to the large scale weather systems that dominate the region including the South and East Asian annual monsoons and the North West Pacific Tropical Cyclone Season that affects South-East Asia.

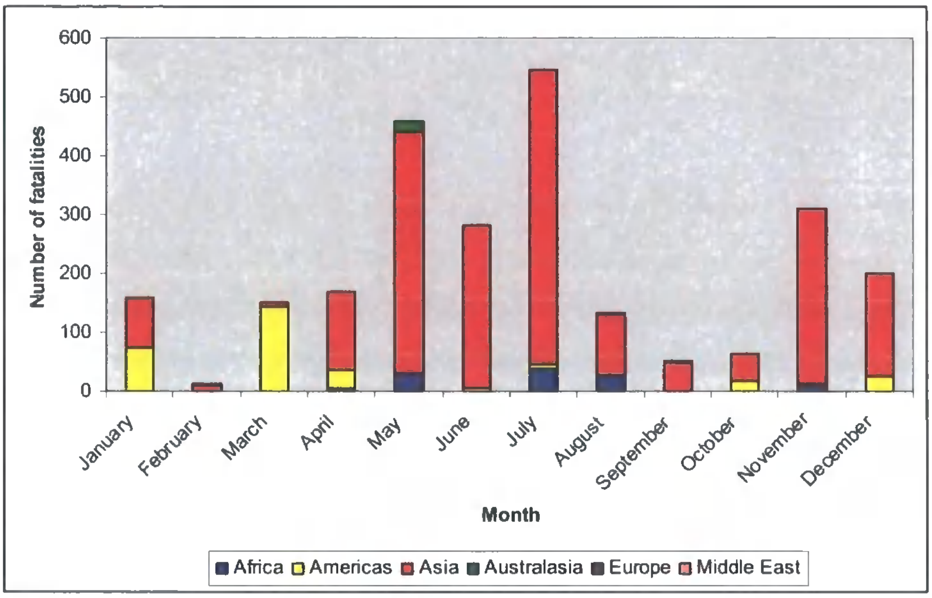


Figure 4.21 The geographical distribution of landslide fatalities in 2003 based upon the landslide database.

Analysing the sub-regional breakdown of Asia, the South Asian area which is dominated by the Indian subcontinent experienced the majority of fatalities in 2003, accounting for 35% of the total recorded (figure 4.22). 89% of the fatalities in South Asia occurred during

May, June and July. These high fatality totals correlate with the high precipitation associated with the South Asian monsoon which in 2003 was 102% of the normal total (NOAA/NCDC, 2004). During the northern hemisphere winter, landslide fatalities were concentrated in the South East Asian region accounting for 25% of the total fatalities recorded for 2003. This period correlates with the occurrence of the North West Pacific tropical cyclone season where rainfall peaks during the month of December.

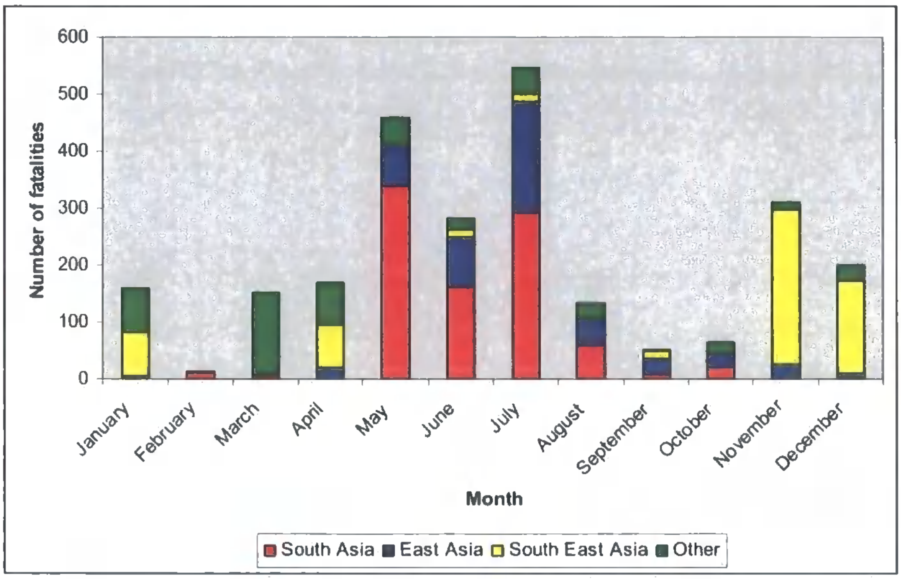


Figure 4.22 The geographical distribution of landslide fatalities in Asia in 2003 based upon the landslide database.

The magnitude-frequency relationship for 2003 has been plotted (figure 4.23), excluding multiple events where the total number of landslides and the total number of fatalities per event was unknown. The magnitude-frequency plot suggests 2003 was dominated by high frequency, low magnitude events, where 88% of recorded landslides caused ≤ 20 fatalities. Analysing the fatality totals of the multiple mass movement events excluded from this analysis, the highest magnitude event in terms of fatalities occurred in Sri Lanka in May killing ~266 people. The absence of higher magnitude events observed in other years suggests that the 2003 death toll from landslide events was probably lower than average.

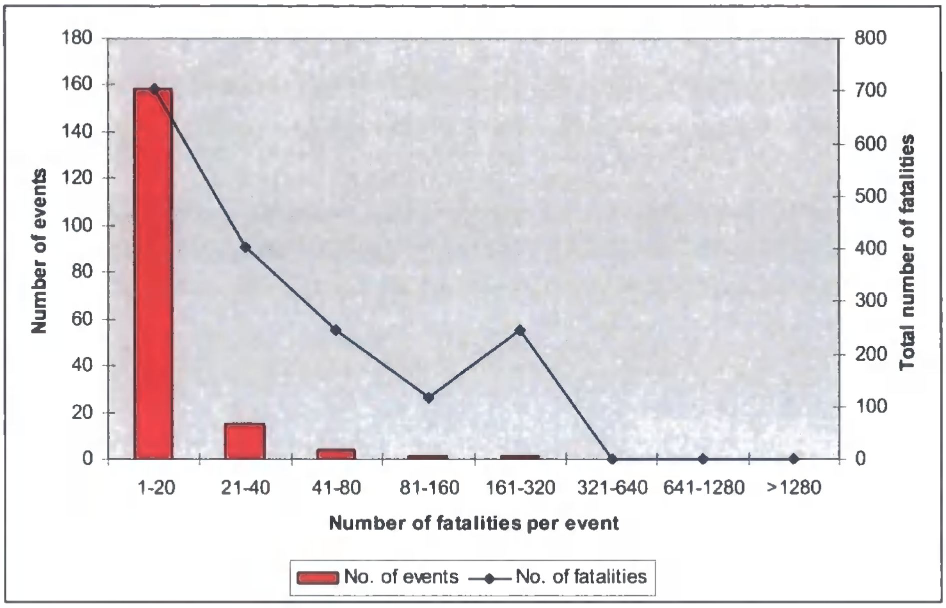


Figure 4.23 Magnitude-frequency plot for the number of deaths per landslide event in 2003. The graph excludes multiple landslide events where the number of fatalities per event was unknown.

The temporal occurrence of fatal landslide events in 2004 has also been analysed (figure 4.24). Unlike 2003, the majority of landslide fatalities occurred during September (47%) when mudslide events in Haiti killed ~3,000 people. Other significant months included May (again dominated by mudslides in Haiti which resulted in ~1,500 fatalities) and November, however the number of fatalities recorded for the months of June and July was far lower (~486 more deaths were recorded during this eight week period in 2003).

Figure 4.25 shows the temporal occurrence of landslide fatalities in 2003 and 2004. The 2004 dataset has been clipped to exclude the two high magnitude events in Haiti which resulted in >1,500 fatalities and previously skewed the dataset. In 2004 43% of fatalities occurred in November following typhoon activity in South East Asia. Typhoon Muifa, Violetta, Winnie and Yoyong triggered extensive landsliding causing ~1063 fatalities predominantly in the Philippines, Indonesia and Vietnam. In 2003 51% of fatalities occurred during the summer monsoon months of May, June and July, while in 2004 only 17% of events occurred during this period. This may be attributed to the above normal strength of the Asian monsoon in 2003 and the below normal (87%) strength in 2004, with some areas in northwest India receiving 22% less precipitation than the mean annual recorded total (NOAA/NCDC, 2004). These findings are explored further in figure 4.26.

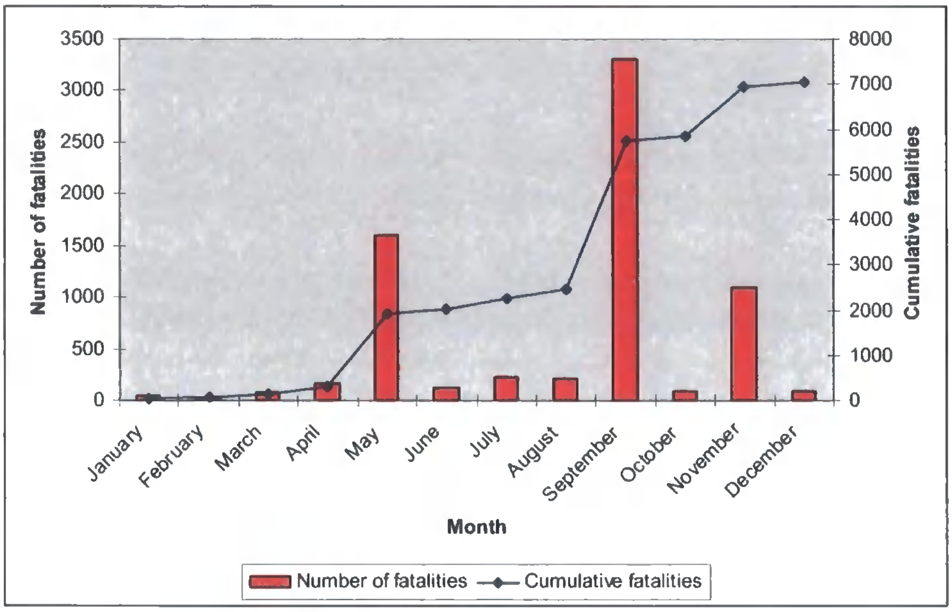


Figure 4.24 The temporal occurrence of landslide fatalities in 2004 based upon the landslide database.

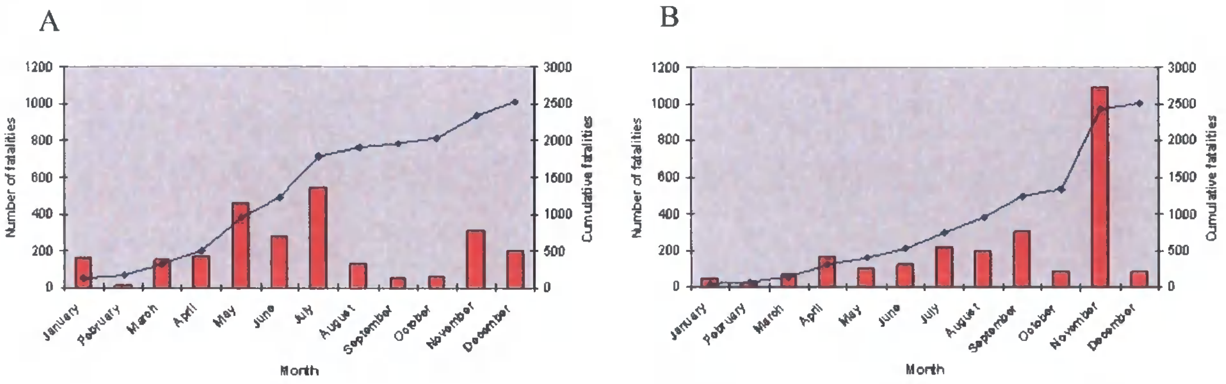


Figure 4.25 The temporal occurrence of landslide fatalities in 2003 (A) and 2004 (B) (author's dataset).

Unlike 2003, the majority of landslide fatalities in 2004 occurred in the Americas. Haiti on the Caribbean island of Dominica experienced high magnitude multiple mass movement events in May and September resulting in ~4,500 fatalities. These events have heavily skewed the geographical distribution of landslide fatalities towards this region (figure 4.26). With this in mind figure 4.27 analyses the geographical distribution of the clipped dataset. The relatively low number of recorded fatalities in May, June and July in South and East Asia may well reflect the weaker monsoon of 2004. By comparison the North West Pacific Tropical Cyclone Season that affects South-East Asia was particularly strong in 2004 triggering a number of events during the southern hemisphere summer months principally in November.

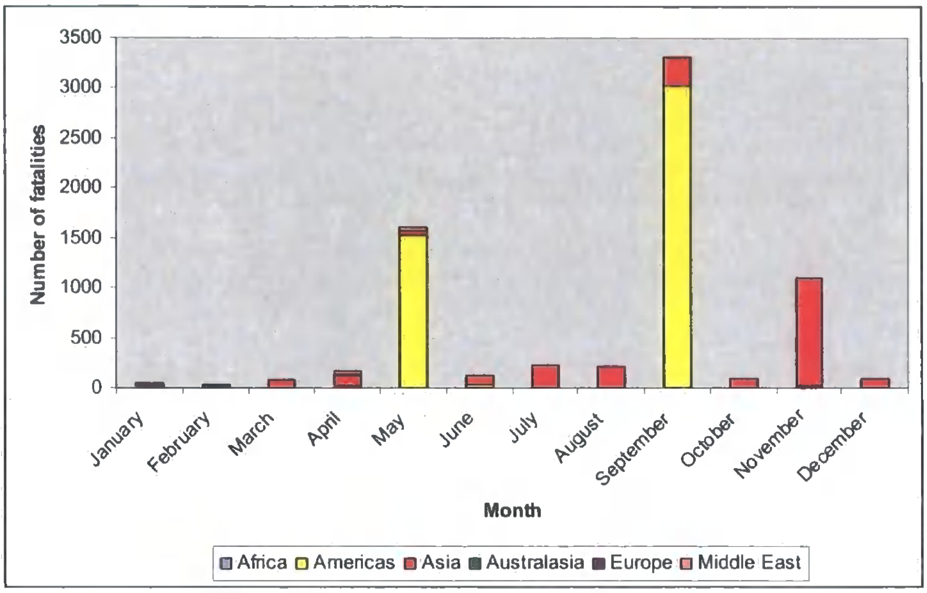


Figure 4.26 The geographical distribution of landslide fatalities in 2004 based upon the landslide database.

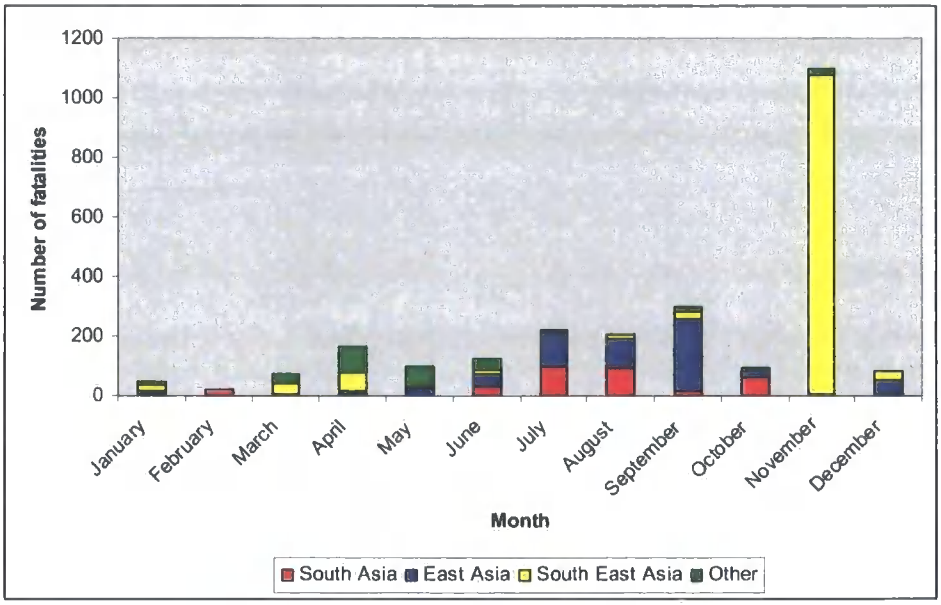


Figure 4.27 The geographical distribution of landslide fatalities in Asia in 2004 based upon the landslide database.

The magnitude-frequency relationship for 2004 excluding multiple events where the total number of landslides triggered and the total number of fatalities per event was unknown is plotted in figure 4.28. As observed in 2003, the majority of landslides occurring in 2004 were high frequency, low magnitude events characterised by ≤ 20 fatalities, following the classic magnitude-frequency for natural hazards. As previously noted, unlike 2003, 2004 experienced two high magnitude events that accounted for 64% of the fatalities recorded. However, due to the weak Asian monsoon in 2004 (NOAA/NCDC, 2005), the recorded death toll is again likely to have been lower than average.

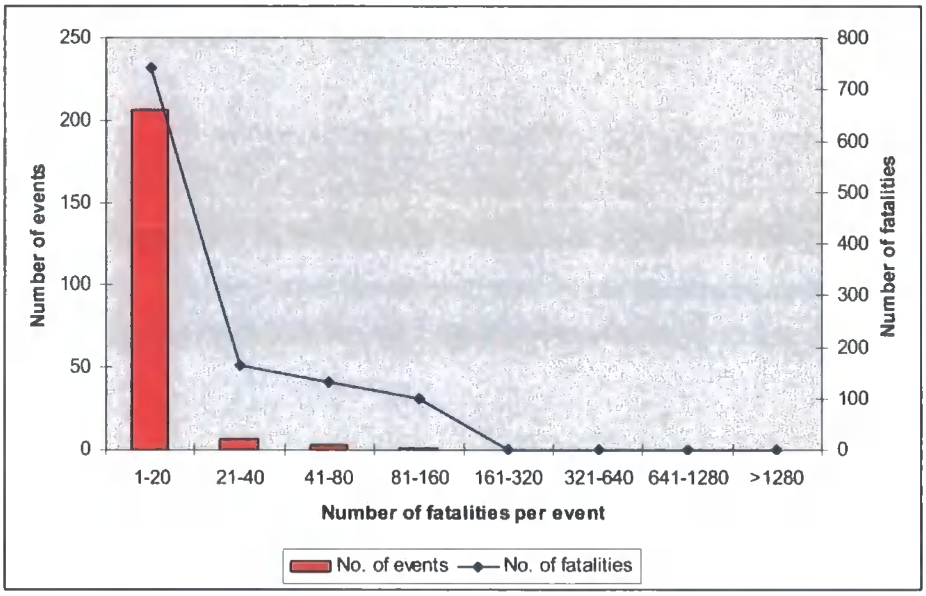
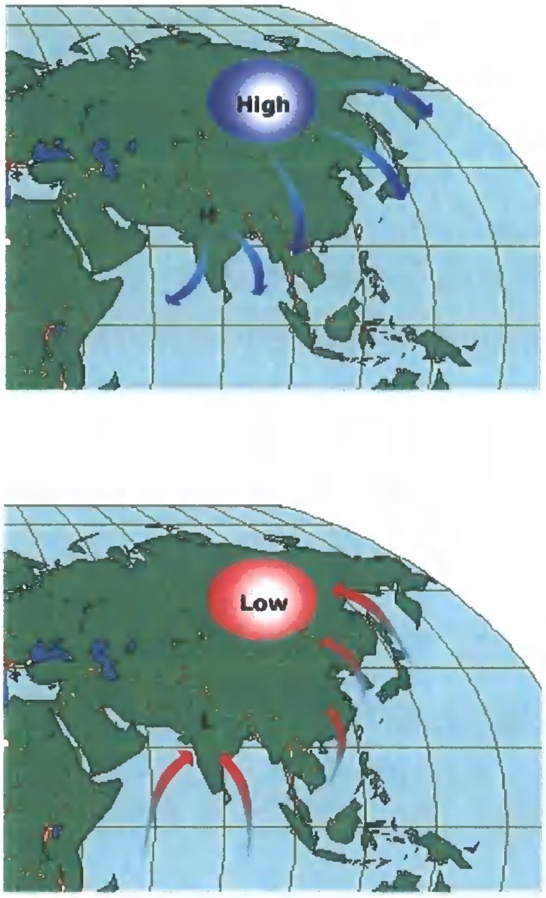


Figure 4.28 Magnitude-frequency plot for the number of deaths per landslide event in 2004. The graph excludes multiple landslide events where the number of fatalities per event was unknown.

4.4.3 Examining the influence of the Asian monsoon system on fatal landslide occurrence

The term monsoon refers to a seasonal change in wind direction which generates cool, dry winters and warm wet summers driven by continental high and low pressure cells which grow and decay over the Asian landmass (Wang *et al*, 2005) The Asian monsoon system is composed of two subsystems, the Indian (South Asian) monsoon and the East Asian monsoon (figure 4.29).



Winter monsoon Between December and February a large, shallow high pressure system develops over continental Siberia, producing a clockwise circulation of air that flows out over the Indian Ocean and South China Sea. These anticyclonic conditions cause air to subside with the movement of dry northeasterly winds from the inland plateau.

Summer monsoon The wind regime reverses as a warm air mass develops above the Asian continent. A shallow thermal low subsequently develops over the continental interior. Moisture bearing winds from the ocean converge with a drier westerly flow causing the air mass to rise. The air is cooled to saturation point generating high intensity precipitation events between June and September.

Figure 4.29 The South and East Asian monsoon systems (Ritter, 2005; Aherns, 2000).

The following analysis focuses upon the South Asian monsoon system.

During the summer months the South Asian monsoonal front migrates in a north westerly direction (figure 4.30)

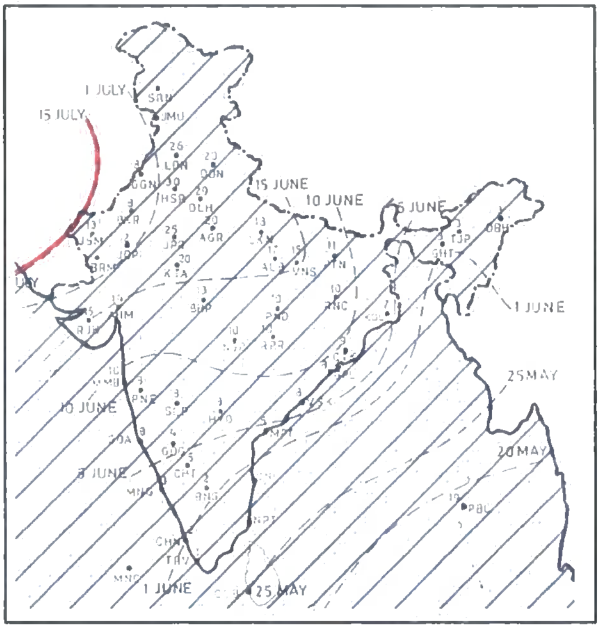


Figure 4.30 The progress of South Asian monsoon rainfall over India (Stephenson *et al*, 2005). The map shows typical dates of onset as the monsoon rainfall treks north, with the red line indicating the northern limit of monsoon. The blue shading identifies the area affected by the monsoon in India.

It was therefore hypothesised that fatal landslide occurrence would correlate with the tracking of the monsoon. Landslides would start to occur in late May on the island of Sri Lanka and in the southern Indian states of Kerala and Tamil Nadu, throughout June for the majority of the Indian subcontinent including India, Nepal, Bhutan and Bangladesh and during the month of July for the north-western Indian states of Rajasthan and Punjab. Figures 4.31 and 4.32 map the climatically triggered fatal landslide events recorded in 2003 and 2004. The landslides are colour coded based upon their month of occurrence.

In 2003 fatal landslide events were recorded in May on the island of Sri Lanka (including one multiple mass movement event which resulted in ~266 fatalities) and during June and July in India. These events correlate with the progression of the monsoonal front. The fatal landslide events are predominantly clustered in Nepal and throughout the northern Indian states of Uttaranchal, Himachal Pradesh and Jammu and Kashmir. These events occurred during July and August, later than expected considering the monsoonal front reaches this region in late June. This may be explained in terms of a lag between the occurrence of monsoon rainfall and the triggering of mass movement events depending upon the prevailing antecedent conditions prior to the onset of the monsoon rains (Gerrard and Gardner, 2000). In addition, Caine and Mool (1982) suggested that a high water table was a primary controlling factor influencing the occurrence of landslide events. These theories offer explanations as to why early heavy rainfalls associated with the seasonal monsoon may not trigger any landslide events and why many landslides occur late in the monsoon season.

In comparison, 2004 was associated with a monsoon deficit in the South Asian region (NOAA/NCDC, 2004). As the monsoon tracked north through India in June, relatively few landslides were triggered, suggesting the monsoon intensity was weak or the onset was delayed. However, mean rainfall data published by the India Meteorological Department

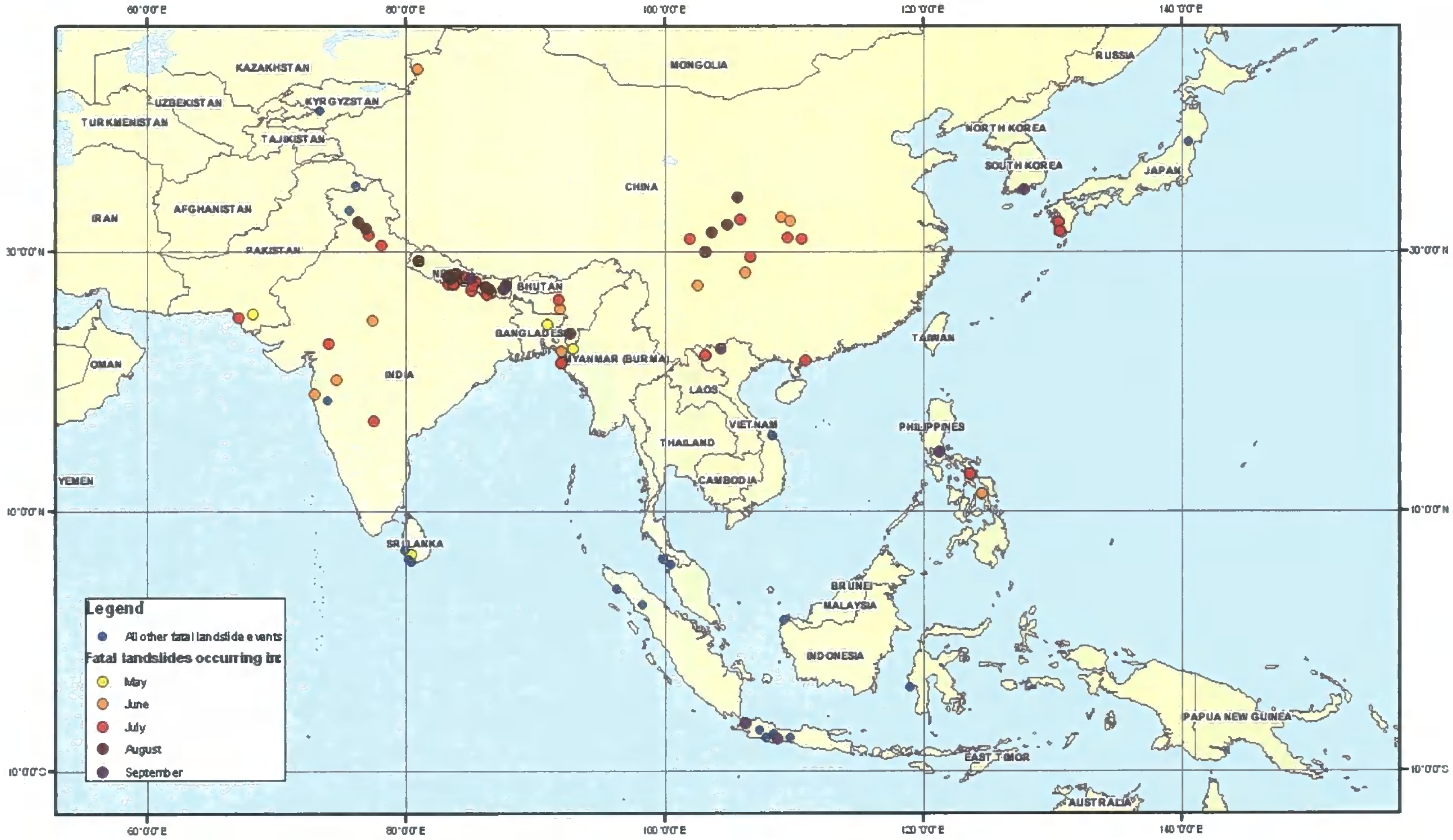


Figure 4.31 Climatically-triggered fatal landslide events in 2003 (author's data set).

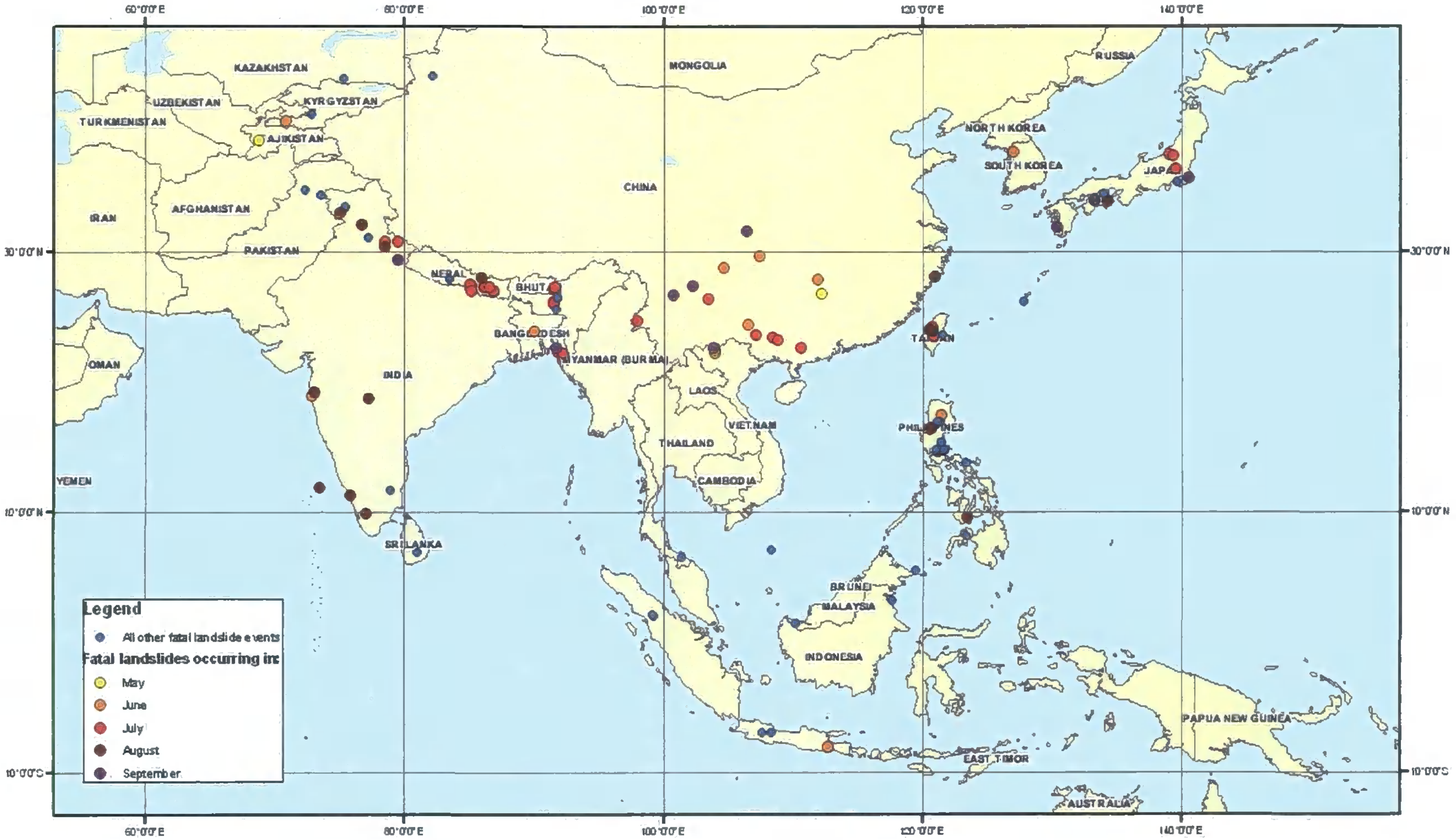


Figure 4.32 Climatically-triggered fatal landslide events in 2004 (author's data set).

shows the weekly rainfall totals for June to be above normal, followed by a deficit throughout July and September (Stephenson *et al*, 2005). As previously noted this may be explained in terms of a lag time between monsoon and landslide activation and hence a number of events occurred in central and southern India, in the north-western states of Rajasthan and Punjab and Nepal during August which was characterised by above normal monsoon rainfall. It should also be noted that there is significant spatial variation in the occurrence and intensity of summer monsoonal rainfall, for example in the Himalaya (Bookhagen *et al*, 2001; Burbank *et al*, 2003). This may explain the observed spatial variations in landslide magnitude recorded within the monsoon zone.

Inter annual variations in the strength and intensity of the monsoon have been observed (Lang and Barros, 2002; Gadgil, 2003; Stephenson *et al*, 2005) (figure 4.33). 2003 was associated with above average monsoonal rainfall for the majority of the subcontinent at 102% of normal (NOAA/NCDC, 2004) while in 2004 India received below average rainfall, with areas in the north east receiving just 50-70% of average monsoon rainfall. Some areas to the west of the subcontinent, the north (adjacent to Nepal) and to the east of Bangladesh received above average rainfall, while the remainder of India was characterised by between 70 and 100% of the normal total (Stephenson *et al*, 2005).

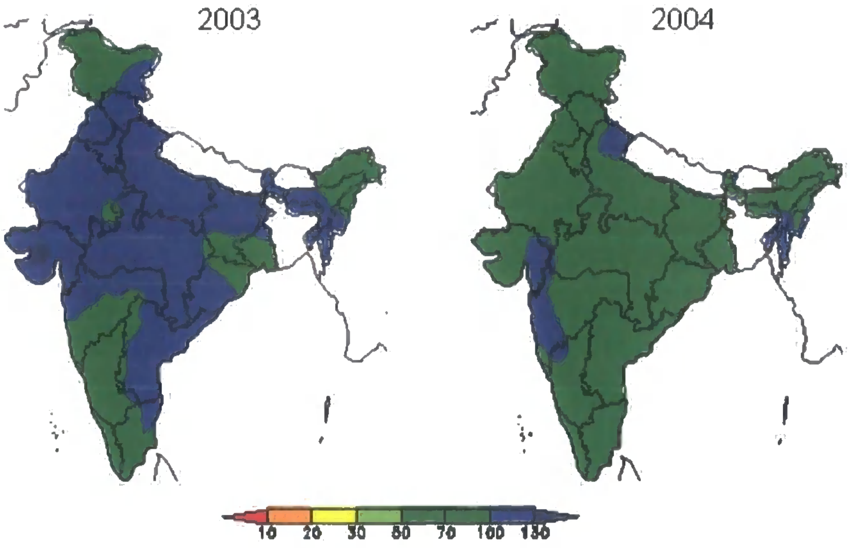


Figure 4.33 Cumulative monsoon rainfall as a percentage of the seasonal normal for the Indian subcontinent in 2003 and 2004 (Stephenson *et al*, 2005). The charts are based on cumulative rainfall data collected from 1 June to 30 September by the India Meteorological Department.

Figure 4.34 illustrates the number of rainfall-induced landslide fatalities recorded for the Himalayan countries of Pakistan, India, China, Bhutan and Nepal between 1994 and 2004. The pronounced increase in the number of recorded fatalities between 2000 and 2002 is explained by the better reporting of events in recent years. However, as this increase is followed by a decrease in the number of recorded fatalities between 2002 and 2004, the pattern of fatalities may also represent the abnormally strong monsoon year of 2003.

Bookhagan *et* al (2005) examined the impact of abnormal monsoon years and their control on erosion in the arid northwest Himalaya. 2002 was classified as an abnormal monsoon year (AMY) for this region with monsoonal rain migrating far into the mountains, reaching regions normally shielded by orographic barriers. During AMY the steep, sparsely vegetated hill slopes characteristic of this arid region become highly susceptible to enhanced erosional processes, including debris flow events. Similar processes may also occur along the entire southern Himalayan mountain front (Bookhagen *et al*, 2005).

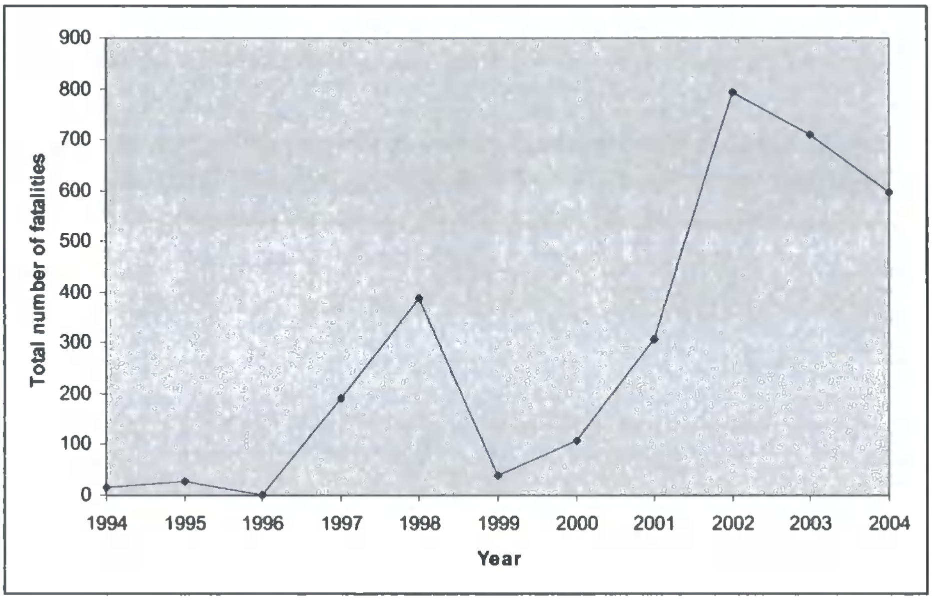


Figure 4.34 The number of rainfall-induced landslide fatalities recorded for the Himalayan countries of Pakistan, India, China, Bhutan and Nepal 1994-2004.

However, while this does offer a potential explanation for the high fatality totals recorded in 2002, it should be noted that figure 4.34 plots the total number of fatalities recorded throughout each country and not just the number of fatalities recorded in the Himalayan region. The peak observed in 1998 (figure 4.34) can be largely attributed to two major catastrophic mass movements that occurred in the Indian Himalayan region that were triggered by high precipitation inputs associated with the annual summer monsoon (Paul *et al*, 2000).

4.4.3 Examining the relationship between the occurrence of El Niño Southern Oscillation events and fatal landslide occurrence

The El Niño Southern Oscillation (ENSO) is a disruption of the ocean-atmosphere circulation system in the Pacific Ocean, caused by changes in atmospheric pressure and ocean temperatures. Links have been made between ENSO and climatic anomalies including most notably, changes in global precipitation (Robinson and Henderson-Sellers, 1999). The influence of ENSO events on the occurrence of landslides has been frequently acknowledged (Gabet and Dunne, 2002, Negecu and Mathu, 1999). Petley *et al* (2005) therefore explored the relationship between landslide fatalities and the occurrence of weak/strong El Niño and La Niña events. However, their findings provided no evidence to suggest that ENSO events influence the occurrence of fatal landslides.

Petley *et al* (2005) focused on the direct relationship between El Niño events and fatal landslide occurrence however, the relationship may be more complex than they proposed. As previously noted there is a clear correlation between summer monsoon occurrence in Asia and fatal landslide activity (figure 4.21). Extensive research has been undertaken examining the relationship between El Niño and La Niña events and their influence on monsoon rainfall (Charles *et* al, 1997; Khole, 2000; Shrestha, 2000; Slingo and Annamalai, 2000; Kawamura *et al*, 2004; Gadgil *et al*, 2004; Pai, 2004; Gupta and Anderson, 2005; Wu and Chan, 2005). Focusing on the South Asian monsoon specifically, it is frequently acknowledged that anomalies in summer monsoon rainfall are linked to El Niño Southern Oscillation events (Verma, 1994; Kane, 1998; Khole, 2000; Gadgil *et al*, 2004). These findings suggest that during El Niño years, the intensity of the Indian summer monsoon rainfall is reduced (Pai, 2004). It would therefore be expected that the occurrence of ENSO events would reduce the number of fatal landslide events triggered by monsoonal rainfall.

Figure 4.35 plots the number of fatalities resulting from rainfall-triggered landslide events in South Asia and these findings have been explored in relation to the occurrence of El Niño and La Niña events. During the 1997/98 El Niño (recognised as the most severe El Niño event of the century (Khole, 2000; Slingo and Annamalai, 2000)) monsoon rainfall totals were above normal and normal (Slingo and Annamalai, 2000) and the number of landslide fatalities increased dramatically. Similarly, a second but relatively weak El Niño event occurred in 2003, a year when the South Asian monsoon was strong (NOAA/NCDC, 2004).

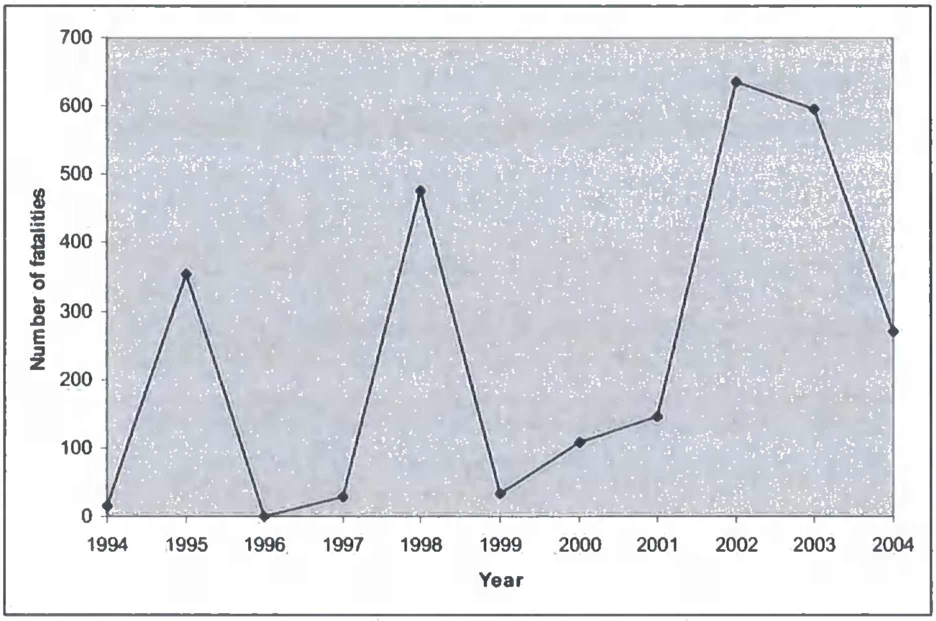


Figure 4.35 The annual trend of landslide fatalities resulting from rainfall-triggered landslide events in South Asia.

These findings suggest El Niño has little impact on monsoon intensity and subsequent landslide activity. Similarly, 1999 was associated with a La Niña event but below average seasonal (June-September) rainfall (IITM, 2005). This rainfall deficit was reflected in the low number of recorded fatalities in 1999 but again, there was no direct link between La Niña and rainfall intensity.

Khole (2000) analysed monthly rainfall data for India between January 1996 and September 1998. Anomalously high precipitation totals were observed for November and December 1997. These findings were attributed to the anomalous warming of the Indian Ocean which occurred during the 1997 El Niño event, which affected the annual cycle of sea surface temperatures in the North Indian Ocean and monsoonal rainfall. These high rainfall totals during the post-monsoon season of 1997 undoubtedly influenced the antecedent moisture conditions (Gerrard and Gardner, 2000), increasing the vulnerability of slopes and the likelihood of failure during subsequent months. This may explain the high landslide fatality totals recorded in 1998 in the South Asian region (figure 4.35).

While it is clear that no correlation is evident, this could be attributed to the following:

- While there is a strong fundamental association between El Niño and deficient Indian summer monsoon rainfall, this relationship was weak between 1991 and 1998 (Pai, 2004).
- Recent research by Kawamura *et al* (2004) suggests that while El Niño events affect Asian summer monsoon variability, this tends to occur during the early summer monsoon period but not during the remainder of the monsoon season.
- Mechanisms triggering inter-annual variations in the intensity and onset of monsoon

rainfall, including links with other phenomena such as El Niño are yet to be completely unravelled and understood (Gadgil, 2003).

- It is impossible to analyse the effect of El Niño on landslide fatalities when the fatality data used prior to 2002 is relatively incomplete.

4.4.4 Long term trends in fatal landslide occurrence

In order to examine longer term trends in landslide occurrence, the 1994-2004 subset was analysed in full. Figure 4.36 shows the magnitude-frequency distribution for this eleven year subset. As previously noted, the quality of the data varies considerably throughout the database. With this in mind the dataset has been clipped to exclude events characterised by <10 fatalities and >1,500 fatalities and multiple mass movement events where the total number of individual events and the number of fatalities per event was unknown. 43% of landslide events resulted in 10-20 fatalities (figure 4.36). Moderately-sized events characterised by 21-40 fatalities per event furnished the highest fatality totals accounting for 21% of recorded fatalities, followed by events in the 81-160 fatalities per event bracket which accounted for 20% of recorded fatalities. The absence of high magnitude multiple mass movement events does distort the magnitude-frequency plot, however the fatality totals associated with these events suggest that the rare, very large events cause the vast majority of fatalities.

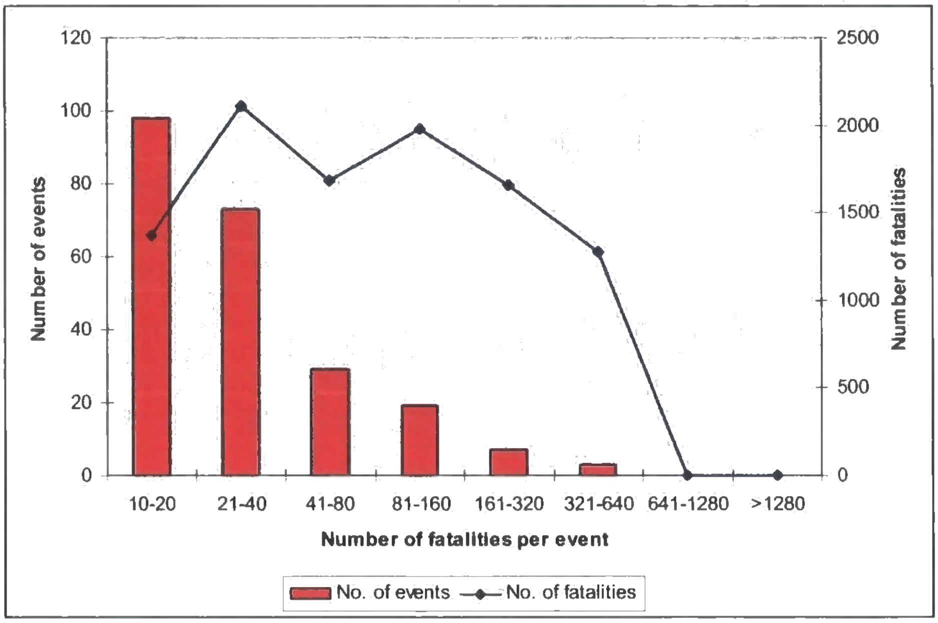


Figure 4.36 Magnitude-frequency plot for the number of deaths per landslide event between 1994 and 2004. The graph excludes events characterised by <10 fatalities and >1,500 fatalities and multiple landslide events where the number of fatalities per event was unknown.

The occurrence of climatically-triggered landslide fatalities excluding events with less than 10 fatalities and more than 1,500 fatalities (figure 4.37) shows an exponential increase in the number of fatalities over time, a trend reported elsewhere (Alexander, 2005; Petley *et al*, 2005; Brabb, 1991).

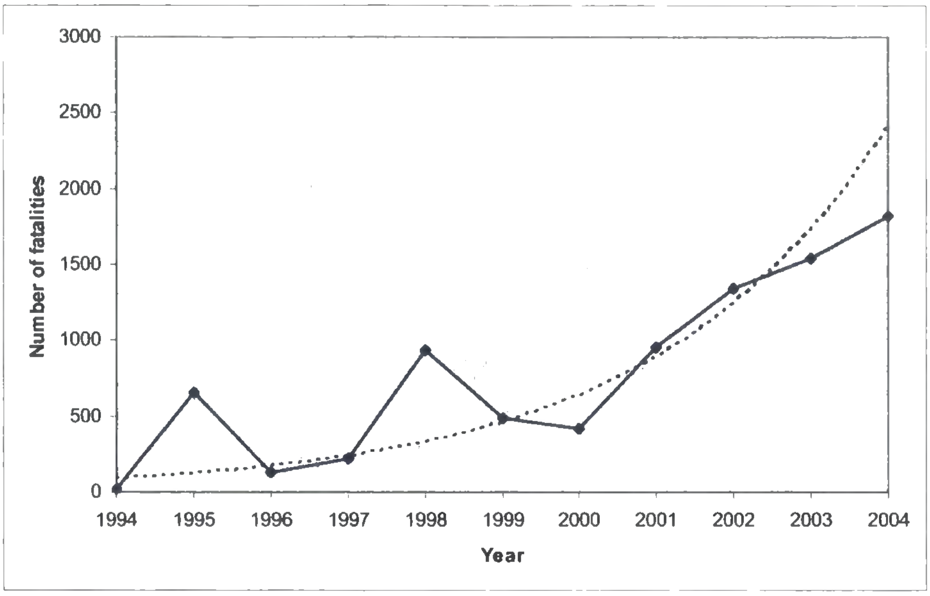


Figure 4.37 The trend in recorded landslide fatalities for climatically-triggered moderately-sized events, 1994-2004 plotted with an exponential trend line.

4.4.5 Global temperature anomaly

Petley *et al* (2005) examined global landslide fatality data in relation to global temperature anomaly data derived from Jones and Moburg (2003) and Parker *et al* (2004). The temperature dataset provides an indication of the difference between surface temperature across both the continents and the oceans in any given year in comparison with the average global surface temperature for the period 1864 to 2004. The estimate of global temperature anomaly is considered to be accurate to about ±0.05°C (Jones and Moburg, 2003). Petley *et al* (2005) observed a strong positive correlation between the number of landslide fatalities per year and the recorded global temperature anomaly with an R^2 value of 0.7885 (figure 4.38 B).

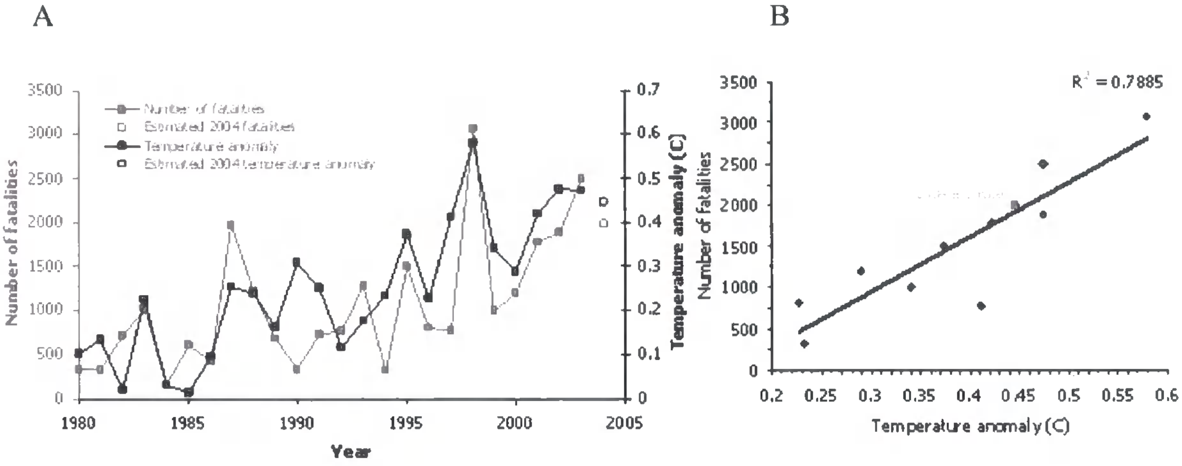


Figure 4.38 A – The trend in recorded landslide fatalities for moderately-sized climatically triggered events plotted with global temperature anomaly (data from Jones and Moberg, 2003) and B – the regression between the datasets for the period 1980-2004.

(Source: Petley *et al*, 2005).

Petley *et al* (2005) acknowledged that the reasons for the observed relationship were unclear and presented a number of possible explanations for the observed trend:

1. Variations in global temperature may cause changes in global precipitation totals which subsequently influence global landslide activity. However, while this seems the most likely explanation, the relationship between global temperature anomaly and global precipitation anomaly is generally considered to be weak (Jones and Moburg, 2003) (figure 4.39).

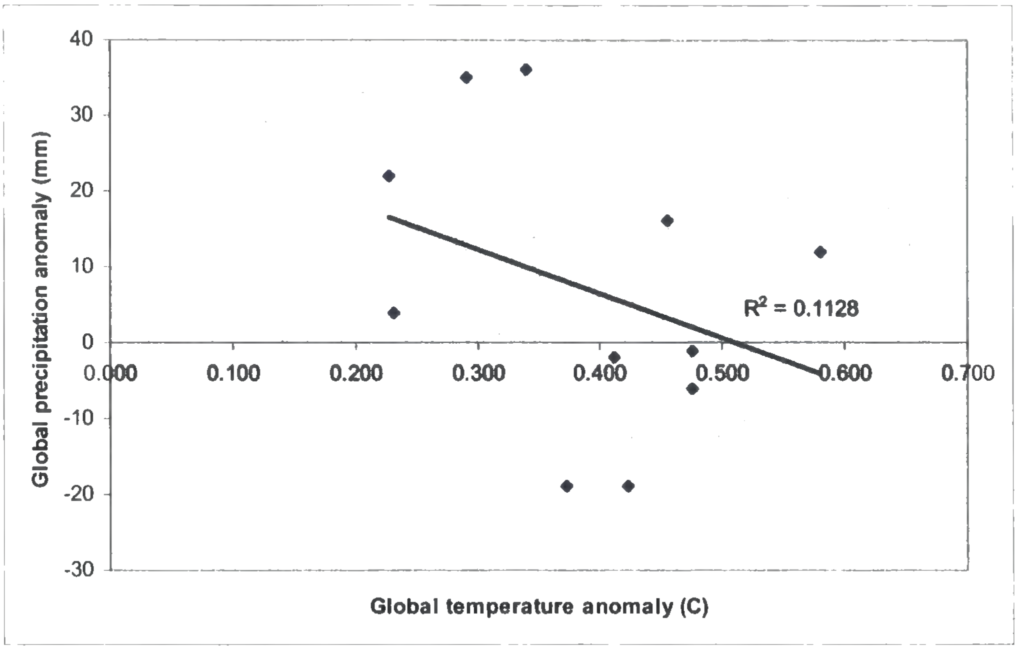


Figure 4.39 The regression between global precipitation anomaly (data from NOAA/NCDC, 2005) and global temperature anomaly (data from Jones and Moberg, 2003) for the period 1994-2004.

2. Variations in global temperature anomaly may cause changes in precipitation intensity with high temperature anomalies associated with high rainfall intensities which are subsequently mirrored in landslide occurrence.
3. Both datasets may be showing a response to an external physical stimulus, for example sun spot cycles (Parker *et al*, 2004) or a socio-economic factor, although the latter is believed to be less likely.
4. The relationship between the two variables may be coincidental.

Since the publication of these preliminary findings, the ILC database has been updated and now includes an estimated figure for the total number of landslide fatalities in 2004. The revised landslide fatality dataset for 1994-2004 has therefore been analysed in relation to the global temperature anomaly dataset (figures 4.40 and 4.41).

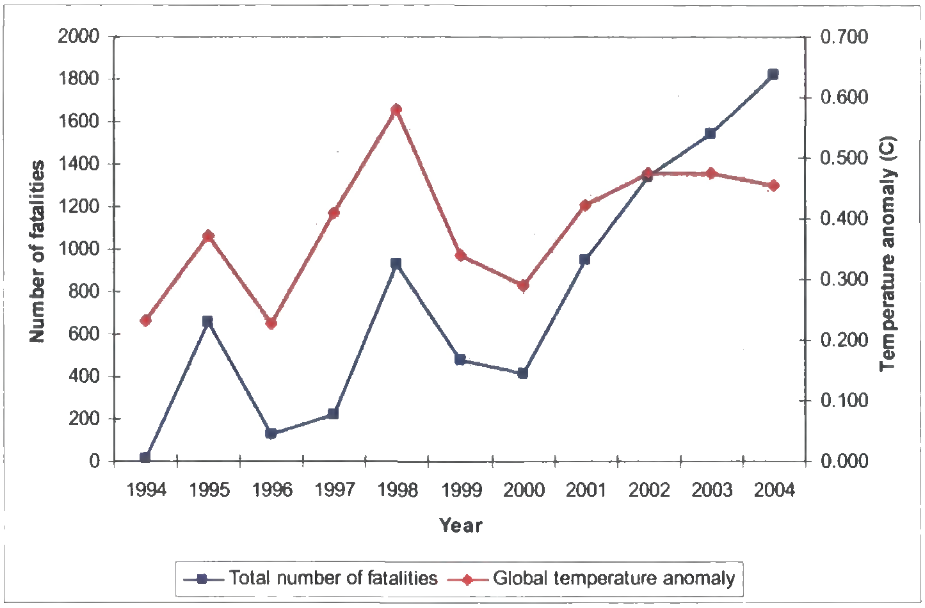


Figure 4.40 The trend in recorded landslide fatalities for climatically-triggered moderately-sized events plotted with global surface temperature anomaly (temperature data from Jones and Moburg, 2003).

The R^2 value has been recalculated at 0.5403 suggesting a less significant correlation between the variables than previously noted. While a relationship is still evident, the pattern appears to change from 2002. Between 2002 and 2004 the temperature anomaly decreased while the number of recorded fatalities is seen to rise. The increase in the number of recorded fatalities may be explained by the more comprehensive landslide database compiled from 2002. This raises questions as to the significance of the correlation because the landslide database is relatively incomplete prior to 2002. Therefore, the correlation observed from 2002 is likely to be more representative of the true relationship between the variables than the first nine years of the dataset. In order to analyse this relationship further it will be necessary to collect landslide fatality data over a longer period, with the aim of making the datasets as complete as possible.

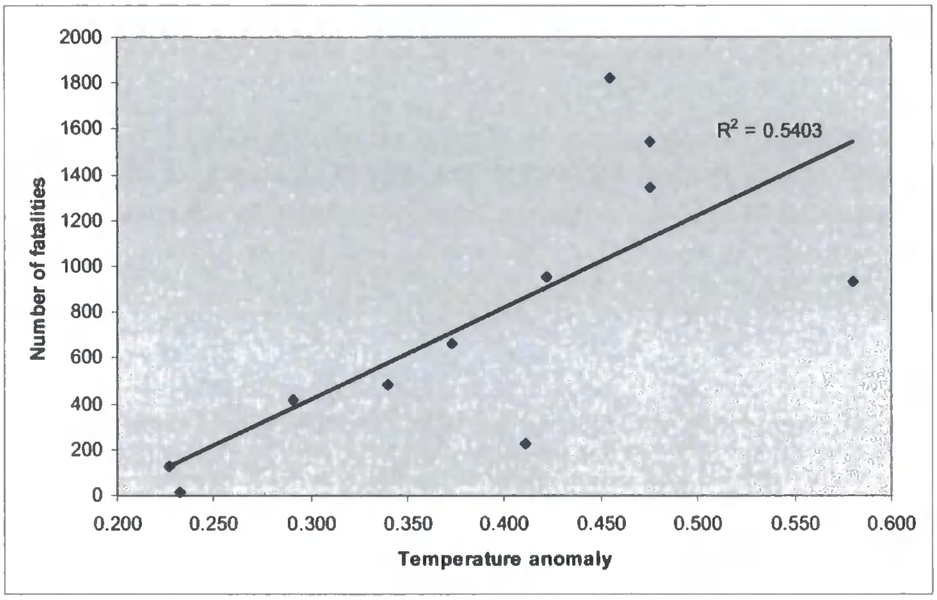


Figure 4.41 The regression between the recorded landslide fatalities for moderately-sized events and global surface temperature anomaly (temperature data from Jones and Moberg, 2003) for the period 1994-2004. The R^2 value for the regression is noted on the graph.

4.4.6 Global precipitation anomaly

As previously noted, the most obvious explanation for the correlation observed is that variations in global temperature cause changes in global precipitation totals which subsequently influence landslide activity. The landslide fatality dataset has therefore been correlated with the annual global precipitation anomaly dataset (National Oceanic and Atmospheric Administration, 2003). This shows the deviation from the global mean annual precipitation total, calculated from data collected between 1961 and 1990.

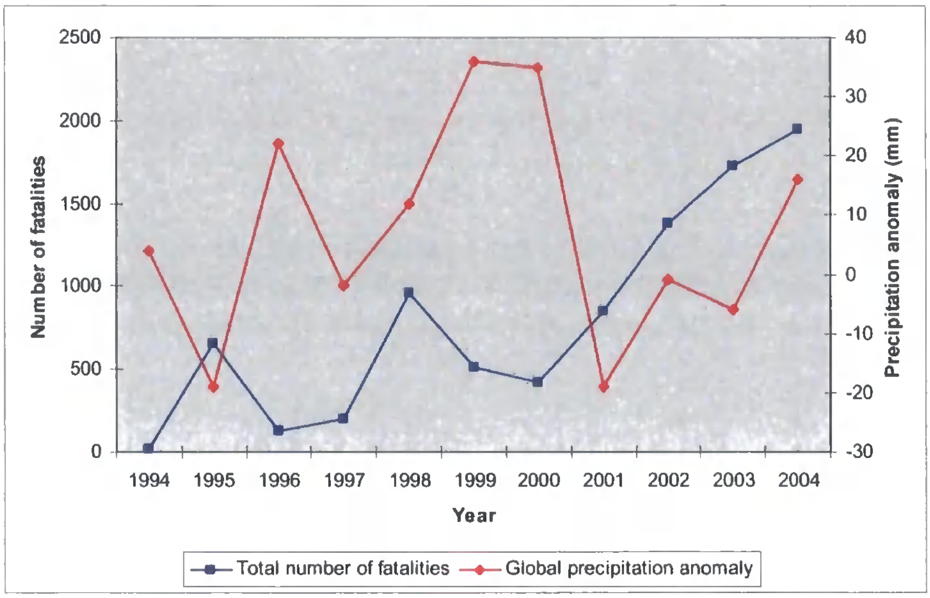


Figure 4.42 The trend in recorded landslide fatalities for moderately-sized climatically-triggered events plotted with the global precipitation anomaly (NOAA/NCDC, 2005).

A strong correlation was anticipated following the observed relationship between the annual monsoon variability in South Asia and fatal landslide occurrence. Figure 4.42 graphs the recorded landslide fatality totals for moderately-sized climatically-triggered events and the global precipitation anomaly, while figures 4.43 shows the statistical regression. The R^2 value was calculated at 0.0402 suggesting there is no significant statistical correlation between the variables and no evidence to suggest that deviations in global precipitation affect the occurrence of fatal landslide events. This is surprising given that the dominant trigger of the fatal landslides recorded within the database was rainfall.

The most likely explanation for the absence of a correlation is that the global mean annual rainfall figure masked regional variations in annual rainfall. For example, 2003 was associated with above average monsoon rainfall in South Asia, while in 2004 the monsoonal rainfall was significantly below normal. However, the global precipitation anomaly data shows the reverse, with mean annual rainfall totals below normal in 2003 and above in 2004.

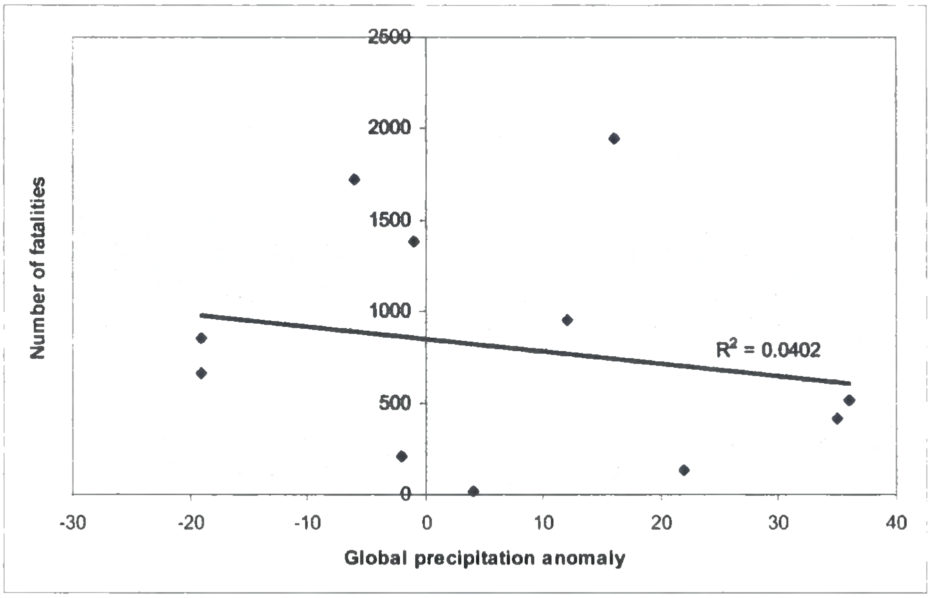


Figure 4.43 The regression between the recorded landslide fatalities for moderately-sized events and global precipitation anomaly for the period 1994-2004 (data from NOAA/NCDC, 2005).

4.4.7 Summary

The analysis suggests that high intensity or prolonged rainfall resulting from large-scale weather systems including the monsoon and tropical cyclones were the dominant triggers of fatal landsliding on a global scale. These findings appear consistent with those of Hovius *et* *al* (2000) and Dadson *et al* (2004). 2003 was dominated by monsoon triggered landslides in South Asia and fatal landslides triggered by tropical cyclones in the North West Pacific. In comparison, in 2004 a number of events were triggered by typhoon activity in South East Asia and hurricanes in the Caribbean.

This sub-chapter has analysed the temporal variations in landslide occurrence focusing specifically upon the impact of the South Asian monsoon system. The following conclusions have been made:

1. Inter-annual variations in the intensity of the South Asian summer monsoon were seen to correlate with the number of landslide-induced fatalities. Strong monsoon years were associated with high fatality totals, while weak monsoon years were associated with low fatality totals.
2. The spatial distribution and temporal occurrence of fatal landslide events in South Asia can be explained by progression of the monsoonal front and prevailing antecedent conditions prior to the onset of the monsoon rains.
3. While it is frequently acknowledged that anomalies in summer monsoon rainfall are linked to El Niño Southern Oscillation events, no such relationship is evident within the dataset. The occurrence of El Niño events revealed no correlation with fatal landslide activity.
4. A strong positive correlation was observed between the number of landslide fatalities and the global temperature anomaly. However, this relationship is not clearly understood and further data collection is required for analysis.

These findings raise important questions regarding the potential impact of future climate change on natural hazard intensity and disaster occurrence.

5 EVALUATING THE LANDSLIDE DATABASE

5.1 Introduction

One of the outlined objectives of this research was to create a workable database that was as comprehensive as possible within the timeframe of this study. To determine how complete and inclusive the database is, simple statistical analyses were undertaken and comparisons were made with other established inventories including the CRED database and the work of Alexander (2005). Finally, the availability of landslide fatality data for Iran, China and Taiwan was discussed with a view to identifying data gaps within the global landslide inventory.

To allow comparisons to be made between the landslide database and other existing datasets no distinction was made between individual and multiple mass movement events.

5.2 Evaluating the completeness of the catalogue

When evaluating the completeness of a database one possible approach is to model the occurrence of events over time using a Poisson distribution (Guzzetti, 2000). This is a discrete distribution which is often used as the model for a number of events occurring over a specific time period (Stanton, 2005). The Poisson distribution can therefore be used to calculate a range of summary statistics including the mean rate of occurrence of fatal landslide events. However, this form of statistical analysis assumes that event occurrence is constant over the selected time period and conditions leading to slope failure may vary significantly over time. As a result Guzzetti (2000) adopted a more simplistic method to evaluate the completeness of the Italian landslide database. This was based upon the visual inspection of cumulative curves of landslide events. This method has been adopted to evaluate the completeness of the global landslide database.

Figure 5.1 graphically represents the cumulative distribution of fatal landslide events between 1994 and 2004. Curve 1 in figure 5.1 shows the yearly cumulative distribution of landslide events resulting in one or more fatalities. There is a dramatic increase in the number of events recorded from 2002 coinciding with the start of the daily compilation of the landslide database.

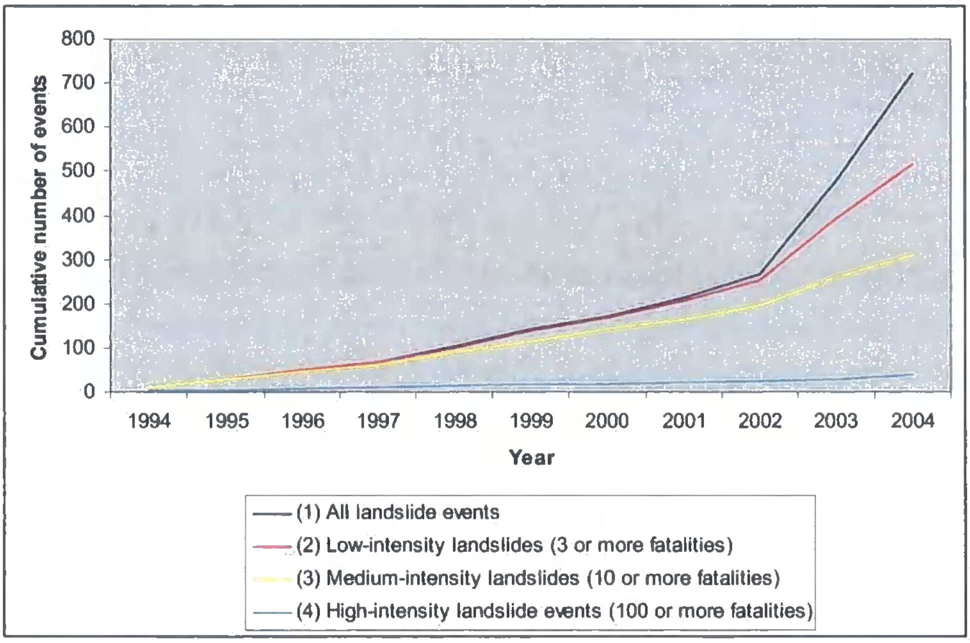


Figure 5.1 The cumulative distribution of fatal landslide events.

As observed by Guzzetti (2000) when analysing the Italian landslide dataset, this change is also evident, but less distinct, in curves 2 and 3 which plot the number of events that resulted in 3 or more fatalities and 10 or more fatalities respectively. This suggests that the completeness of the catalogue varies with the intensity (indicated here by the number of fatalities) of the landslide event.

The graph indicates that for high-intensity events resulting in 100 fatalities or more, the landslide database is reasonably complete and comprehensive throughout, with only a slight overall increase in the number of high-intensity events recorded between 1994 and 2004. For low-intensity events (≥3 fatalities) the catalogue is only reasonably complete after 2002. While medium-intensity events (≥10 fatalities) have been far more comprehensively recorded than the low intensity events, there was still an increase in the number of events captured in the database from 2002.

5.3 Evaluating the landslide database in relation to other established landslide inventories

In addition to the cumulative distribution analysis, comparisons have also been made between the landslide database and other established global and national landslide inventories. The aim of this analysis was to determine the number of events that were not recorded, with a view to determining the effectiveness of current data collection methods.

5.3.1 The Centre for Research on the Epidemiology of Disasters EM-DAT Database

Figure 5.2 plots the number of fatal landslide events recorded per year within the CRED database in comparison to the author's dataset. Between 1994 and 2004 CRED recorded 163 fatal landslides. In comparison, the author's dataset recorded 722 events. The number of fatal landslide events recorded per year within the CRED database was relatively consistent reflecting the data collection methods adopted. The landslide database was compiled as an historic archive until 2002. From this point and as previously noted, there was a dramatic increase in the number of recorded events, reflecting the detailed daily collection of landslide fatality data.

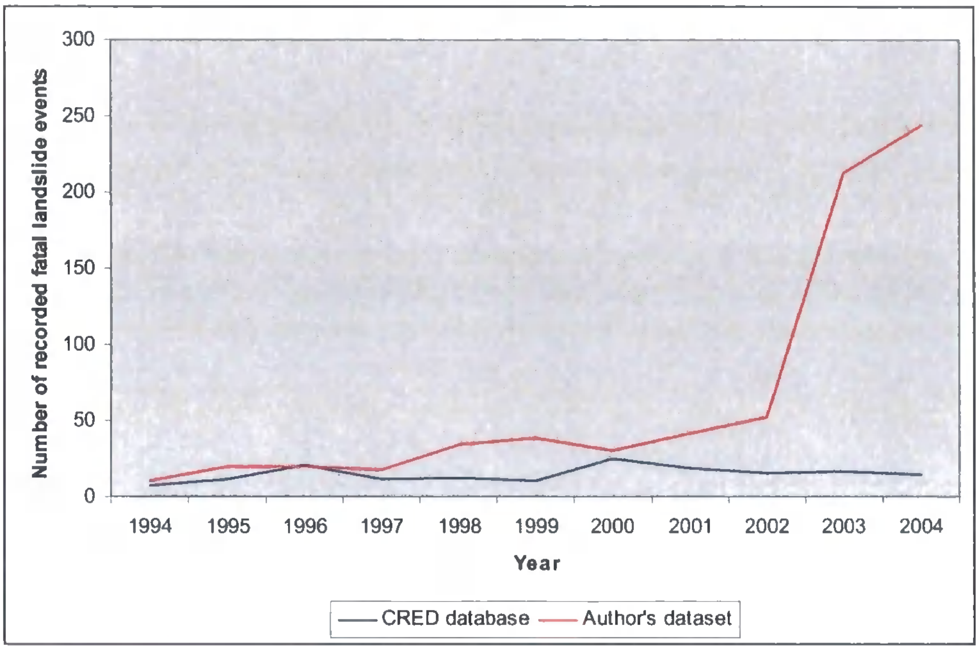


Figure 5.2 The number of fatal landslide events recorded per year within the CRED database in comparison to the author's dataset.

In 2003 and 2004, the landslide database recorded ~457 fatal events in comparison to the 32 recorded by CRED. This can to a certain extent be explained by the criteria used for inclusion as only landslides resulting in 10 or more fatalities were included in the EM-DAT database. However, if all landslides associated with ≤10 fatalities were excluded from the author's dataset, the number of events recorded for 2003 and 2004 was still substantially higher (~100 events) than CRED's published figure of 32. These findings are encouraging and suggest that current data collection methods are proving reasonably effective in terms of data capture.

Figure 5.3 compares the number of landslide fatalities recorded per year between both datasets. In total, CRED recorded 7895 fatalities while >23,000 landslide related fatalities were recorded in the author's dataset excluding the 30,000 fatalities associated with the 1999 Venezuela mudslides. With the exception of 1996, the number of landslide fatalities recorded per year was lower in the CRED database. During 1996, two fatal landslide events in China were missing from the author's dataset, while fatalities were recorded for Norway and Korea that were missing from the CRED database. Excluding events associated with <10 fatalities did account for some of the observed discrepancy in the fatality totals, however approximately 7500 more fatalities were recorded for 2003 and 2004 in the author's dataset.

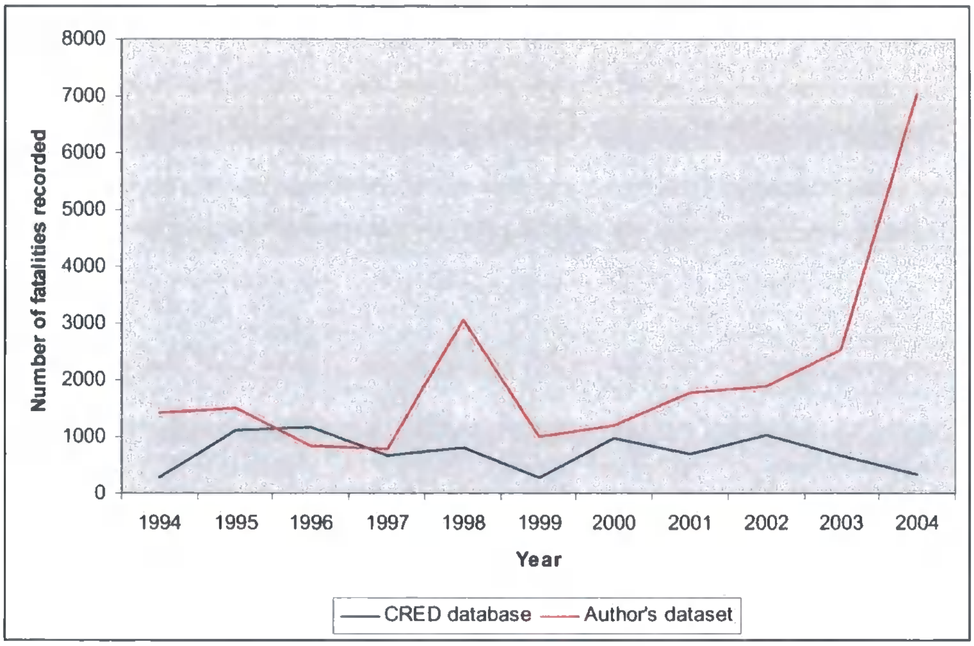


Figure 5.3 The number of landslide fatalities recorded per year within the CRED database in comparison to the author's dataset. The author's dataset has been clipped to exclude the 1999 Venezuela mudslides which skewed the dataset with 30,000 fatalities.

5.3.2 Alexander's (2005) landslide fatality database

Alexander's (2005) database of 'significant' landslide events was compiled over 8.75 years between August 1993 and May 2002. During this time 352 landslide events causing significant damage, casualties or fatalities were recorded along with 40,702 landslide related deaths. In order to make comparisons with the author's dataset, reference was made to the long term ILC database to extract landslide fatality data for 1993. Over the same time period, the author's dataset recorded ~42,689 fatalities. The majority of events occurred in Asia (43%) followed by the Americas (36%) and as observed within the author's dataset, the majority of fatalities occurred in the Americas (89%). Such consistency between datasets is encouraging and suggests that a relatively comprehensive database of global landslide fatalities has been compiled.

5.4 National case studies

Landslide fatality data from three specific countries has been analysed. These include China, Iran and Taiwan. These countries have been selected for further investigation with a view to evaluating the completeness of the landslide database and to identify and explain any observed data gaps.

5.4.1 China

China undertook a large number of landslide related projects during the International Decade of Natural Disaster Reduction. The projects, sponsored by the United Nations, included a nation-wide landslide investigation, the findings from which formed part of China's landslide hazard reduction strategy. In a recent conference symposium, Yin and

Wang (2005) published a series of landslide fatality statistics which estimated that between 800 and 1,000 people are killed annually by landslide disasters in China.

The author's dataset recorded 86 fatal landslide events throughout China between 1994 and 2004 with an additional 17 multiple landslide events resulting in a total of 2,250 fatalities. In comparison, over the same time period, Yin and Wang (2005) recorded >10,700 fatalities. Using 1994-2003 data, the mean number of fatalities per year can be calculated for both data sets. Based upon Yin and Wang's data, an average of 903 fatalities occurred each year in comparison to 205 fatalities per year based upon the landslide database. An annual comparison has been made between the published annual fatality statistics and the data recorded within the landslide database (figure 5.4).

The following observations were made:

- Only 21% of the landslide fatalities reported by Yin and Wang (2005) between 1994 and 2004 were recorded in the landslide database.
- The landslide database shows a clear increase in the number of landslide fatalities between 1999 and 2004. This could be attributed to better reporting following the UN sponsored landslide project.
- Comparatively, Yin and Wang report an overall decline in fatalities from 1998 (with the exception of the year 2000) to 2004. This decrease may reflect the successful implementation of China's landslide hazard reduction strategy.
- In 2003 51% of the landslides reported by Yin and Wang were recorded in the landslide database. This increased to 61% in 2004, an increase of 17% from 1999. These figures

suggest that compiling the landslide database on a daily basis has enabled the capture of a greater number of fatal landslide events.

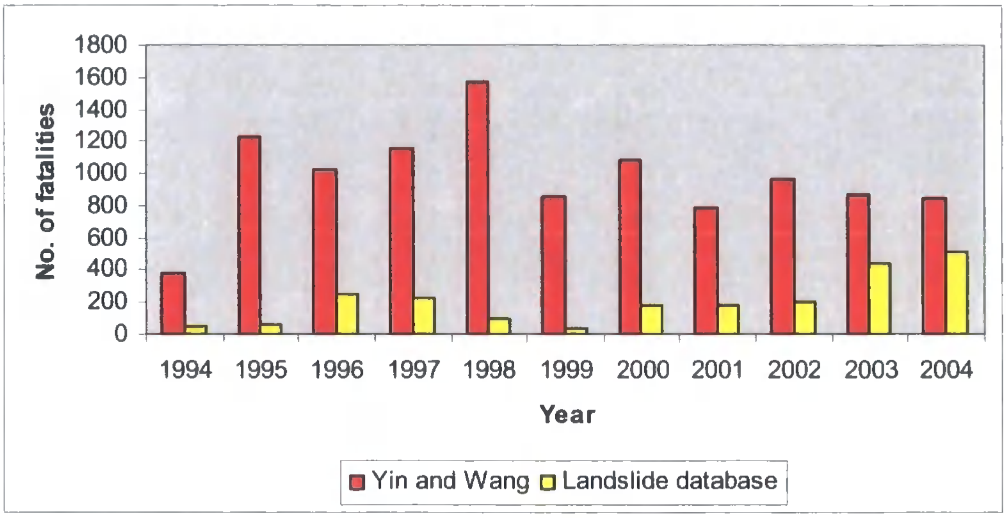


Figure 5.4 The number of landslide related deaths recorded for China between 1994 and 2004.

These findings raise questions as to why the landslide database failed to capture so many events. Possible explanations include language difficulties and the use of different criteria for the recording and reporting of fatal landslide events. Landslide fatality figures may not be published to the outside world reflecting China's culture of secrecy. Alternatively, the published figures may be an exaggeration of the real situation in China in an attempt to exaggerate the effectiveness of the landslide hazard reduction strategy. This is not a typical error as collecting landslide fatality data in China is particularly difficult to attain, for example the use of characters makes textual searching all but impossible. The findings from this study suggest that the data and data availability are far better for most other countries.

In terms of the spatial distribution of recent landslide disasters in China, Wen *et al* (2005) observed that fatal landslides occurring between 2001 and 2004 were largely concentrated in the mountainous areas in the southwest and the hilly terrains that characterise the southern provinces. The provinces of Chongqing, Sichuan, Yunnan and Hunan experienced the greatest number of fatal landslide events. These findings affirm those from earlier studies (for example, Tianchi, 1989) and the spatial distribution pattern observed within this thesis (figure 4.1).

5.4.2 Iran

Iran was also selected as a case study for further investigation. According to the landslide database only four fatal landslide events were recorded in Iran between 1900 and 2004 with only two of these landslides associated with earthquake events. This is surprising as Iran is one of the most seismically active regions in the world (Ghayoumian and Shoaei, 1997). The Alpide Earthquake Belt extends from west Portugal eastwards along southern Europe towards South East Asia and the Pacific Ocean, crossing Iran. In this linear zone of earthquake activity, 95% of the world's earthquakes occur (Ghayoumian and Shoaei, 1997). As a result earthquake activity is one of the most common landslide triggering mechanisms. For example, approximately 120 landslides were triggered by the 1990 magnitude 7.7 earthquake in Manjil (Ghayoumian and Shoaei, 1997) resulting in 137 fatalities (author's dataset). A subsequent magnitude 6.4 event occurred in 2004 resulting in further 28 landslide-induced fatalities (author's dataset). These low fatality numbers are problematic given the high numbers of deaths that have been reported for earthquakes with one Iranian in 3,000 likely to die during an earthquake event (Bilham, 2004).

A possible reason for the absence of landslide fatality data for Iran is reporting. In 1997 Ghayoumian and Shoaei published a key paper examining the spatial distribution of landslides and their controlling factors within Iran. They noted that very little was written and reported about landslides until the International Decade of Natural Disaster Reduction and the occurrence of the fatal 1990 Manjil earthquake. Ghayoumian and Shoaei (1997) recognised that thousands of landslides have occurred in remote areas within Iran, however these were seldom reported and no published data was available for them. This prompted extensive research including the development of a national landslide database system and a landslide hazard zoning project based upon guidelines outlined by UNESCO (1990). The outputs of the project are starting to emerge including a landslide distribution map of the country and information regarding the economic impacts of landslide events (National Geoscience Database of Iran, (2005). However, no fatality or casualty statistics have been cited. This may reflect a project in its infancy or may simply suggest that while the landslide frequency is high, the human impact is low.

5.4.3 Taiwan

According to the landslide database between 1994 and 2004, 14 fatal landslide events and 2 multiple mass movement events occurred on the island of Taiwan. In total these events caused ~487 fatalities. Major events included the multiple landslides triggered by Typhoon Toraji in July 2001 which resulted in 240 deaths and the Chu-feng Ershan rock slide triggered by the magnitude 7.7 Chi-Chi earthquake which killed ~90 people in September 1999. The fatal landslides recorded within the database for Taiwan resulted in between 1 and 240 fatalities, with the majority of events occurring in rural areas. Capturing such low magnitude events within the database suggests a certain level of comprehensiveness (section 6.2). However, interviews undertaken with Professor Fu-Shu Jeng, Department of Civil Engineering, Professor Jin-Chun Lin, Department of Geography and Professor Hongey Chen, Department of Geosciences at the National Taiwan University, revealed some additional fatal landslides that were not previously recorded within the landslide database. At least 1 fatal landslide and 4 fatal debris flows were triggered by Typhoon Herb in 1996 resulting in a total of 26 fatalities (Lin and Jeng, 2000). The absence of these events from the database may reflect the data collection methods used to compile the inventory prior to 2002 (section 4.1.3).

Natural hazards including landslides are heavily logged within Taiwan (Chen, *pers comm.*), particularly following the implementation of the national hazards mitigation programme in 1997 (NCDR, 2005). Hazard databases do exist, for example the National Fire Agency which reports deaths caused by natural hazards and the National Disasters Prevention and Protection Commission (Jeng and Lin, *pers comm.)*. However, these databases are in Chinese highlighting problems associated with language and communication. In addition, while Jeng (*pers comm.*) has access to government hazard data as an academic/engineer he recognises that not all hazard fatality data may be available within the public domain. The absence of a database in English made it impossible to analyse Taiwan's landslide inventory and to evaluate the completeness of the landslide database analysed within this study. Many of the available journals focused on the large-scale landslide events, for example Ts'ao-Ling (figure 3.2) or the general impact of an earthquake or typhoon event in Taiwan. As a result, these sources provided little additional information for the database. Overall, the findings from the fieldwork undertaken in Taiwan highlighted the difficulties associated with obtaining landslide fatality data even in a country where natural disasters are heavily monitored and mitigation plans are in place.

5.5 Summary

The landslide database has been analysed to asses the completeness of the global inventory. The findings are encouraging and suggest that the fatality database is reasonably comprehensive from 2002. However, the completeness of the catalogue was seen to vary with the magnitude of the landslide disasters with events associated with high fatalities (≥100) being more comprehensively recorded than low intensity events (≥3 fatalities). In comparison to other global landslide inventories, more events were recorded in the landslide database suggesting that the methods used are proving reasonably effective in terms of data capture. In addition, there was consistency in the spatial patterns observed within this thesis and Alexander's (2005) findings suggesting a more detailed and reliable picture of global landslide occurrence has been generated. As anticipated there are gaps in the database where fatality data may be difficult to source, fatalities may go unreported/unrecorded, the data may be unpublished or may not be available in English. However, it is hoped that the compilation of national landslide inventories following the proposal by UNESCO (1990) will provide more comprehensive information and reliable fatality statistics at a national scale which can be combined to develop a meaningful global database.

6.1 CONCLUSION

"Connectivity between physical and social systems is a fundamental characteristic of natural risk" (Hufschmidt *et al*, 2005a: 375).

The aim of the research presented here was to analyse the spatial patterns and controls governing the global occurrence of fatal landslide events. To achieve this, six hypotheses were generated and the landslide database was used to empirically test these statements. The findings summarised below show some surprising results which challenge current understanding of the global spatial distribution and temporal occurrence of fatal landslide events.

1. The frequency of fatal landslide events is increasing with time.

It is clear from the research undertaken that landslide disasters continue to impose substantial human losses and fatalities worldwide. In addition, following the analysis of >700 fatal landslides, it can be observed that the frequency and magnitude of these fatal landslides has increased with time. The database shows that global landslide events follow a classic magnitude-frequency distribution (Alexander, 2005) (figure 4.4), dominated by high frequency, low magnitude events which account for 51% of the landslides recorded, but only 5% of the total recorded fatalities. In comparison, the rare exceptional high magnitude events characterised by ≥1001 fatalities accounted for the majority of deaths.

In general, debris and mudflows were associated with the highest fatality totals (>1,500 fatalities), while rockfalls were generally associated with <10 fatalities per event. In terms of spatial occurrence (figures 4.1 and 4.5), the majority of fatal landslides occurred within Asia (74% of landslides and 70% of the multiple mass movement events). However, the American region furnished the highest death toll accounting for 76% of the total fatalities. Asia's landslide inventory was dominated by high frequency, low magnitude events, while the America's experienced the reverse.

2. *The occurrence of landslide fatalities is a function of the level of development of a country, with lower levels of development being associated with high numbers of fatalities.*

Notwithstanding the fact that the number of recorded deaths is lowest in high income countries, the findings suggest that globally landslide fatalities predominantly occur in middle income countries. While this implies the occurrence of fatal landslides is not simply a function of the level of development of a country, it is necessary to consider whether such spatial patterns would emerge if a longer time series was examined or if more detailed information was available in areas where landslide fatality data is currently sparse. It could be argued that the Venezuelan mudslides have skewed the dataset, highlighting the vulnerability of middle income countries and/or the use of alternative development indicators (other than the World Bank's income classification) may yield different results.

3. *The occurrence and impact of fatal landslide events is greater in urban than in rural areas.*

Understanding vulnerability to landslide hazards requires more than merely quantifying exposure (Small and Naumann, 2001). Megacities and other large urban centres are susceptible to large scale events however they are not exclusively vulnerable to landslide disasters *per se* (Cross, 2001). Indeed between 1994 and 2004, 74% of the fatal landslides recorded occurred within hamlets, villages and other sparsely settled areas which accounted for 41% of the total fatalities.

4. *Areas that have been subject to severe land degradation are more prone to the occurrence of fatal landslide events.*

While few of the recorded landslide events were associated with deforestation, road construction or land-use change, it is not possible to preclude their influence on fatal landslide occurrence. The findings may, to an extent, reflect sensationalised media reporting which focuses on and exacerbates the human mismanagement of the environment (Ives, 2004). However, land use change is highly site specific and can be viewed as a precursor rather than a trigger of landslide activity. In addition, these factors change with time (Hufschmidt *et al*, 2005a) making it difficult to assess the impact of land degradation on landslide activity at the global scale. Indeed at the recent International Geomorphology Conference, Hufschmidt *et al* (2005b) presented a paper on the evolution of landslide risk in New Zealand. The paper highlighted the importance of time and how natural processes, elements at risk and their vulnerability vary temporally (figure 6.1). It is therefore

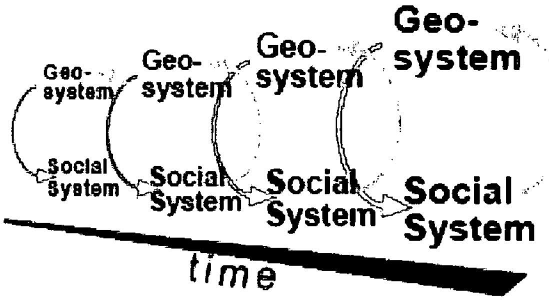


Figure 6.1 The interaction between the geosystem and the social system through time (Hufschmidt *et al*, 2005a).

important to understand the history of a specific geomorphic system to assess the factors controlling instability (Hufschmidt *et al*, 2005a).

5. Fatal landslides are concentrated in areas characterised by high relative relief, high precipitation inputs and/or areas subject to seismic shaking.

Primarily controlled by the geophysical environment, landslide occurrence was broadly influenced by relief and orogenesis along with other associated predisposing and preparatory factors including weathering and tectonic uplift (Glade and Crozier, 2005). While these factors influence slope stability, the landslide database clearly points to precipitation as the dominant triggering factor initiating mass movement. 94% of all recorded fatalities were the result of rainfall-induced landslides irrespective of area. By comparison earthquake activity was a relatively infrequent trigger initiating only 4% of the recorded slope failures and accounting for only 4% of the recorded fatalities. While this was unexpected given the findings of Keefer (1984), Rodriguez *et al* (1999), Hovius *et al* (2000) and Dadson *et al* (2004), it would seem that seismic shaking acts more as precursor, pushing a stable slope into a marginally stable state by enhancing susceptibility, but without causing movement directly (Lin *et al*, 2004; Hufschmidt *et al*, 2005a).

6. Human/social factors are more significant than physical parameters in determining the occurrence of fatal landslides.

There has been a clear shift in the conceptualisation of natural disasters from physical or natural events towards integration with human systems (Alcántara-Ayala, 2002; Weichselgartner, 2000). This research has highlighted the importance of the geophysical environment which, within the field of natural hazard research, has largely been overshadowed by the focus on human vulnerability. Undoubtedly, changes in frequency, intensity and duration of meteorological events are the dominant factors determining the spatial and temporal occurrence of landslide disasters between 1994 and 2004. While a number of early studies suggested that the long-term frequency of natural events has remained more or less constant with time (Chapman, 1994; Uitto, 1998), recently published research has challenged this conclusion (Emanuel, 2005; Webster *et al*, 2005; Ashrit, 2005). 87% of fatal landslide events were triggered by high intensity and prolonged rainfall associated with tropical cyclones and the seasonal monsoon. Increases in tropical cyclone intensity (Emanuel, 2005; Webster *et al*, 2005) and monsoon strength (Ashrit *et al*, 2005) are therefore of particular concern. In addition, while the future impact of climate change is unknown, the strong correlation between landslide fatality totals and global temperature anomaly (figures 4.40 and 4.41) raises a number of questions, particularly as variations in global temperature appear to be a major factor governing the occurrence of landslide fatalities worldwide (Petley et al 2005).

While socioeconomic and demographic trends can broadly explain the vulnerability of society to hazards and subsequently the spatial distribution of disasters, the geophysical environment is the overriding factor influencing the occurrence of mass movement events. It can therefore be concluded that human/social factors are not more significant than physical parameters in determining occurrence of fatal landslides, but it is the complex interaction and connectivity (Cutter, 1996; Hufschmidt, 2005a) between both systems which determines the temporal and spatial occurrence of fatal landslide events on the global scale.

6.2 Original contribution and extension to previous research

The primary objective of this research was to map the global distribution of fatal landslide events and to challenge current assumptions regarding the spatial distribution and causative factors of fatal landslide events. A series of maps have been generated and detailed spatial and temporal analysis has been undertaken. While numerous landslide studies have been undertaken at the local and regional scales, little had been done to assess the spatial and temporal occurrence of landslides globally and despite proposals by UNESCO to generate a global landslide inventory, there were no evident outputs. Instead, general understanding was largely based upon anecdotal evidence; with essentially no reliable, quantitative data to justify these observations.

Prior to undertaking this research, Alexander's (2005) study was the only comprehensive analysis of the spatial distribution of landslides on a global scale. However, while the key physical landslide triggers were identified, little was done to analyse the temporal variations in landslide occurrence and the focus was largely on issues of human vulnerability. While the landslide database is far from complete and a number of problems have been identified regarding data collection and locating the landslide events, progress has been made in terms of understanding the global landslide problem and the broad processes active over a number of sites that are contributing to slope failure.

6.3 Recommendations for further research

The research undertaken is part of an on-going project to examine landslide distribution on a global scale. It has generated many more questions than it has answered and demonstrated that there is still a long way to go before a global model can be achieved to explain observed trends in landslides occurrence. Based upon the research findings, the following areas have been identified for further research.

The length of the dataset used within this study was only eleven years. This raises important questions regarding data representivity, particularly when considering recurrence intervals of high magnitude events and long term spatial and temporal patterns in landslide occurrence. The landslide database for 2003 and 2004 is thought to be a relatively comprehensive and complete dataset with the recording of the global occurrence of fatal landslide events on a daily basis. To understand the spatial distribution of landslides, it is essential to continue compiling this database and to identify specific countries where there is an incomplete landslide record. Local sources of information including interviews with local people, with emergency services personnel and with local / regional government officers would undoubtedly help to establish the true impact of each landslide in terms of lives lost and to establish the occurrence of fatality-inducing and non-fatal events within recent years. This can only be achieved through the creation of detailed and comprehensive national landslide inventories.

The findings from the research have highlighted the importance of large-scale weather systems in influencing the occurrence of fatal landslide events. The temporal analysis thus far has focused largely upon the South Asian monsoon system and the impact of inter-annual variations in the strength and intensity of the seasonal monsoon on landslide occurrence. However, following the publication of research suggesting that the frequency and intensity of tropical cyclones has increased over the last 30 years (Emanuel, 2005; Webster *et al*, 2005) further research and analysis is essential on this topic.

In addition, correlation between global temperature anomaly and the number of landslide induced fatalities is poorly understood. More research is necessary to explore the correlation between global temperature anomaly and precipitation intensity and to investigate the influence of external factors such as anthropogenic activity. As observed in chapter 5 the relationship between temperature anomaly and annual landslide fatality totals does change in 2003 and 2004 along with the quality and completeness of the database. It is therefore important to continue developing the landslide dataset to enable the analysis over a longer time period, with a view to assessing the implication of the strong association observed between 1994 and 2002.

As discussed in chapter 3, a number of issues have been raised regarding the locational accuracy of the landslide events. This is an important issue if the database is to provide meaningful results. A data sensitivity test could be undertaken whereby the spatial distribution of fatal landslides is analysed, using the landslide data in its highest available resolution. The resolution/accuracy of the locations will then be decreased, the model will be run and the spatial relationships re-analysed. This could be repeated, each time decreasing the resolution of the data, to determine the effect locational accuracy has on the spatial distribution of the landslide events and our understanding of the forcing factors of the distribution.

This study has focused on five key physical parameters: relative relief, mean annual precipitation, susceptibility to erosion, global seismic hazard and population density. It would be of interest to analyse the relationship between landslide occurrence and other variables including slope angle (a fundamental predisposing factor influencing slope stability) and vegetation cover (to assess the impact of large-scale deforestation). This would help to broaden our understanding of the spatial patterns and controls governing the occurrence of fatal landslides.

While physical factors can be quantified, analysing the influence of human factors such as poverty, deprivation and levels of development are more complex and intangible. An attempt was made to analyse the relationship between levels of economic development (World Bank, 2005) and fatal landslide occurrence. An alternative method would be to adopt a deductive approach whereby comparisons are made between the number of recorded landslides in two countries characterised by similar physical attributes, for example Nepal and Bhutan. Differences in fatality totals would then be analysed in relation to a range of social, economic and political factors including levels of deforestation, road construction and levels of poverty and deprivation. These findings could subsequently be used to infer the levels of human influence on landslide occurrence, enabling the analysis of the connectivity between the physical and social systems.

'The understanding of hazards and disaster involves two broad areas of enquiry. We are concerned with the actual damages, their incidence and distribution; and how to explain them' (Hewitt, 1997: 21).

The increased frequency of landslide events that result in human fatalities is difficult to explain with respect to any one specific factor although population growth and climate change appear to be increasing vulnerability to such natural events (Hanson and Roberts, 2005). This trend will probably continue meaning that research into the landslides, which are one of the most destructive of geological processes (Brabb, 1993,) must be undertaken to allow mitigation of this fatal hazard.

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APPENDIX 1 **The Landslide Database** **Key** 🟥 Multiple landslide events

Date	Continent	Country	Location	Latitude	Longitude	Fatalities
05/02/1994	SE. Asia	Philippines	Davao Del Norte Province			4
09/03/1994	C. Asia	Kyrgyzstan	Small village near **Osh**, Usgen region (Tosoi)	40.5294	72.7900	51
(mid)/04/1994	S. America	Brazil	Amazon tin mine			19
14/04/1994	C. Asia	Kyrgyzstan	**Osh**, Jalal-Abad Region	40.5294	72.7900	111
27/05/1994	S. Asia	India	Sabaragamuva Province			15
06/06/1994	S. America	Colombia	Paez earthquake - Dublin, Irlanda, **Toez**, and Belalcazar	2.8000	-76.0667	1109
01/07/1994	E. Asia	China P Rep	Yunnan Province			48
06/08/1994	SE Asia	Viet Nam	Lai Chau province			21
22/09/1994	SE Asia	Philippines	**Bacolor**, Porac (Pampanga province)	15.0139	120.6539	23
01/12/1994	C. Africa	Ethiopia	Unknown			22
		8 landslides	2 multiple events			1423
07/01/1995	S. America	Peru	**Puno**	-15.8333	-70.0333	20
17/01/1995	E. Asia	Japan	**Nikkawa,** Nishinomiya, Nr Kobe	35.8667	140.6833	34
17/01/1995	E. Asia	Japan	**Nishinomiya,** Hanshin Urban Region	34.7167	135.3333	34
07/02/1995	S. America	Brazil	**Sao Paulo**	23.5333	-46.6167	42
27/03/1995	S Asia	Afghanistan	Kurluk Zir Kutal (**Daraim** district, Badakhshan Province)	36.8667	70.3833	354
31/05/1995	S. America	Brazil	**Salvador**, Estado de Bahia	-12.9833	-38.5167	86
03/06/1995	S. Asia	India	Mizoram State			40
10/06/1995	S. Asia	Nepal	**Okhaldhunga**	27.3167	86.5000	85
10/06/1995	S. Asia	Nepal	**Dailekh**	28.8333	81.7333	
10/06/1995	S. Asia	Nepal	**Kaski**	28.2667	83.8833	
10/06/1995	S. Asia	Nepal	**Jajarkot**	28.7000	82.2333	
10/06/1995	S. Asia	Nepal	**Lamjung**	28.2000	84.3667	
19/06/1995	S. America	Colombia	**Santa Rosa de Cabal**, Dosquebradas	4.8681	-75.6214	17
30/06/1995	SE Asia	Malaysia	Genting Highlands (Near **Kuala Lumpur**)	3.1667	101.7000	20
13/07/1995	Europe	Turkey	**Senirkent**	30.1044	30.5486	50
(mid)/07/1995	E Asia	China	village, S/W China			26
17/08/1995	N. Africa	Morocco	Atlas Mountains			230
12/09/1995	S. Asia	India	Kulla region (Himachal Pradesh)			400
28/09/1995	C. Asia	Russia	Nazran Region			17
09/10/1995	E. Asia	China P Rep	Zhejiang			37
		19 landslides	1 multiple event			1492

Date	Continent	Country	Location	Latitude	Longitude	Fatalities
10/02/1996	E. Asia	Japan	Hokkaido - tunnel between **Furubira** and Yoichi	43.2500	140.6333	20
20/02/1996	S. America	Brazil	**Rio De Janeiro**	-22.9000	-43.2333	96
09/04/1996	S. America	Bolivia	Shanktytown (**La Paz**)	-16.5000	-68.1500	40
21/04/1996	S. America	Brazil	Salvador City	12.9833	-38.5167	26
29/04/1996	S. America	Brazil	Recife			23
05/05/1996	S. America	Colombia	Danubio			5
31/05 - 03/06/1	E Asia	China P Rep	Laojinshan, Yunnan			226
20/06/1996	Europe	Norway	**Finneid**, Nordland	66.1833	13.8167	4
26/07/1996	E Asia	Korea Rep	Near **Chorwon**, Gangwan	38.2500	125.2500	19
08/08/1996	Europe	Spain	Near **Biescas**, Huesca	42.4167	0.4333	84
30/08/1996	SE Asia	Malaysia	Pos Dipang (Perak State) near **Kampar**	4.3000	101.1500	50
17/09/1996	SE Asia	Philippines	South			12
27/09/1996	Australasia	Australia	Gracetown, **Cowaramup** Bay, Banbury, WA	-33.8667	115.0833	9
30/09/1996	S. Asia	India	Karnataka, Andhra Pradesh, Maharashtra			48
03/10/1996	SE Asia	Indonesia	Batam Isl.			23
28/11/1996	SE Asia	Philippines	Catanduanes (**Mindanao**)			33
28/11/1996	S. Africa	South Africa	**Dealesville**	-28.6667	25.7667	34
02/12/1996	E. Asia	China P Rep	Guizhou Province			23
06/12/1996	E. Asia	Japan	Otari village, **Nagano**	36.6500	138.1833	14
24/12/1996	Australasia	Papua New Guinea	Wajunda Village			38
		19 landslides	1 multiple landslide events			827
10/01/1997	Europe	Italy	Pozzano, **Naples**	40.8333	14.2500	4
18/01/1997	Europe	Italy	Brevna Glacier, Mont Blanc Range			2
19/01/1997	N. America	USA	**Kitsap**, Rolling Bay, Bainbridge Island, Washington	47.5831	-122.7072	4
20/02/1997	S. America	Peru	**Taraco** district, Puno province	-15.3000	-69.9667	300
20/02/1997	S. America	Peru	**Pusi** district, Puno province	-15.4333	-69.9333	
20-21/04/1997	Australasia	Micronesia	Sokehs District, Pohnpei			19
09/06/1997	E. Asia	China P Rep	Meigu CountySichuan Prov.			147
09/06/1997	S. Asia	India	**Gangtok** (city)	27.3333	88.6167	28
26/06/1997	C. America	Mexico	**Huautla De Jimenez**, Oaxaca	18.1333	-96.8500	12
17/06/1997	S Asia	Pakistan	Jabar Kund, **Mansehra**	34.3333	73.2000	24
10/07/1997	E. Asia	Japan	Izumu City, **Kagoshima**	31.6000	130.5500	21
15/07/1997	E. Asia	China P Rep	Sichuan, Xingwen			79
31/07/1997	Australasia	Australia	**Thredbo**	-36.5000	148.3167	19
06/08/1997	S. Asia	India	Darjeeling Hills			23

Date	Continent	Country	Location	Latitude	Longitude	Fatalities
10/08/1997	S. Asia	Nepal	Sagarmath, Koshi, Mechi			20
27/08/1997	E Asia	Taiwan	Lincoln Mansions, **His-chih**, Taipei County	25.0667	121.6500	28
31/10/1997	Europe	Azores	**Ribeira Quente** Village, Sao Miguel	37.7333	-25.3000	29
23/11/1997	C. Africa	Uganda	**Mbale** Region	-0.7000	30.6333	20
		18 landslides	0 multiple landslide events			779
14/01/1998	S. America	Peru	**Santa Teresa** near Machu Picchu	-13.1322	-72.5906	14
21/01/1998	S. Africa	Mozambique	Milange district (Zambezia province)	-16.0986	35.7700	87
29/01/1998	S. America	Peru	**Choco**	-16.6833	-151.4500	31
06/02/1998	Australasia	French Polynesia	**Tahaa** (lat/long for the approximate centre of the island)	-16.6667	-151.5000	10
11/02/1998	S. America	Bolivia	Mocotoro - 140 miles north west **La Paz**	16.5000	-68.1500	60
23/02/1998	C Asia	Tajikistan	east of Dushanke			11
27/02/1998	S. America	Peru	The Andes, Aobamba			40
04/03/1998	S. America	Ecuador	Rio Canas, Manabi Povince			17
05/03/1998	S. Asia	India	Himachal Pradesh			26
10/03/1998	S. America	Peru	**La Laja**	-13.8333	-75.5500	16
10/03/1998	S. America	Peru	**La Laja**	-13.8333	-75.5500	
13/03/1998	S. Asia	Pakistan	**Reshian**	34.2583	73.8222	13
02/04/1998	Middle East	Iran	**Ab Kenareh**	30.3469	51.1339	81
12/04/1998	S. America	Ecuador	**La Guajira**			12
25/04/1998	Australasia	French Polynesia	**Tahaa Is.** (lat/long for the approximate centre of the island)	-16.6667	-151.5000	13
25/04/1998	Australasia	French Polynesia	**Raiatea Is.**	-16.8333	-151.4167	
26/04/1998	C. Asia	Tajikistan	Gam District			100
28/04/1998	S. America	Ecuador	**Pachinche** Adentro	-1.1000	-80.4000	8
30/04/1998	S. America	Ecuador	**Bahia de Caraquez**	-0.6000	-80.4167	10
03/05/1998	S. America	Colombia	**Caldas**, Nr Medellin, Antioquia	6.0900	-75.6375	4
05/05/1998	Europe	Italy	**Sarno**, Campania	40.8167	14.6167	161
21/05/1998	E Asia	China P Rep	Guangdong, Sichuan, Hunana, Fujian, Zhejiang, Hubei, Gansu, Guangxi Prov.			100
03/06/1998	S. Asia	India	**Badarpur**, Assam	24.9000	92.6000	48
21/06/1998	S. Asia	India	Sandhighat, **Guwahati**	26.2500	91.7500	21
08/07/1998	S. Asia	Nepal	**Thankot**	27.8667	83.1333	5
/08/1998	S Asia	India	**Dehra Dun**	30.3167	78.0333	8
14/08/1998	S Asia	India	**Garhwal**, Gutpkashi, Uttarakhand	29.8000	78.6167	69
18/08/1998	S Asia	India	**Dharchula**, Uttarakhand	29.8500	80.5333	210
19/08/1998	S Asia	India	**Rudraprayag**	30.2833	78.9833	37
26/08/1998	C. America	Guatemala	Chujuyu, Las Graditas, **Pachoj**	14.9333	-91.1167	51

Date	Continent	Country	Location	Latitude	Longitude	Fatalities
26-31/08/1998	E Asia	Japan	Taiyo-no Koni, **Nishigo-Shimo**, N. Japan	38.6500	141.1500	8
28/09/1998	C. America	Mexico	Tenextepango, **Ayala** (Morelos State)	18.7500	-98.9833	12
12/10/1998	SE Asia	Malaysia	**Selangor**	3.3500	101.2500	2
30/10/1998	C. America	Nicaragua	Casita Volcano, **El Porvenir**, Rolando Rodriguez, Departmento de Chinandega	12.6333	-87.1500	1680
22/11/1998	S. America	Colombia	La Catorce, near town of **Quipama**	5.5222	-74.1808	104
		27 landslides	7 multiple landslide events			3069
07/01/1999	SE Asia	Indonesia	Pupuan, Bali Isl. 20 miles north of **Denpasar**	-8.6500	115.2167	33
02/04/1999	C. Asia	Tajikistan	southern Tajikistan'			9
01/04/1999	SE Asia	Philippines	South of Philippines			19
04/04/1999	SE Asia	Indonesia	Bali Isl.			3
09/04/1999	S. America	Colombia	**Cienaga**, Choco, Cauca, Cordoba (others all provinces)	5.4000	-73.3000	25
15/04/1999	S. America	Colombia	Argelia, western Colombia			5
15/04/1999	S. America	Colombia	Argelia, western Colombia			
21/04/1999	SE Asia	Philippines				14
09/05/1999	N. America	USA	Sacred Falls, **Hauula**, Hawaii	21.6106	-157.9108	8
10/05/1999	SE Asia	Philippines	**Medina** (Mindanao Isl.)	8.9122	125.0244	10
10/05/1999	SE Asia	Philippines	**Lugait** (Mindanao Isl.)	8.3369	124.2603	
10/05/1999	SE Asia	Philippines	**Talisayan** (Mindanao Isl.)	8.9964	124.8842	
21/05/1999	S. America	Brazil	**Salvador**	-12.9833	-38.5167	25
13/06/1999	N America	USA	**Yosemite**	37.3467	-84.8247	1
16/06/1999	E. Asia	China P Rep	Sichuan			23
07/07/1999	C Asia	Tajikistan				23
13/07/1999	Europe	Romania	**Riu-de-Mori**, SW Romania	45.4833	22.8500	15
19/07/1999	S Asia	India	**Mumbai**	18.9750	72.8258	7
25/07/1999	S Asia	India				10
26/07/1999	E Asia	China P Rep				7
27/07/1999	SE Asia	Indonesia	Long Iram district, Kutai, East **Kalimantan**	1.6167	109.1833	9
02/08/1999	E Asia	South Korea	Hwachon, Kwanwon	38.1075	127.7144	10
03/08/1999	SE Asia	Philippines	Cherry Hills, **Antipolo City** (Manila suburb)	14.5864	121.1753	59
11/08/1999	S. Asia	Bangladesh	**Bandarban**	22.2000	92.2167	7
15/08/1999	S. Asia	Bangladesh	**Chittagong**	22.3636	91.8033	10
01/09/1999	S Asia	India				12
12/09/1999	E Asia	S Korea				5
13/09/1999	SE Asia	Philippines	Nord du pays			13
21/09/1999	E Asia	Taiwan	**Ts'ao-Ling**	23.5867	120.6906	29

Date	Continent	Country	Location	Latitude	Longitude	Fatalities
21/09/1999	E Asia	Taiwan	**Chu-Feng Ershan**	23.8500	120.8100	90
21/09/1999	E Asia	Taiwan	Shui-Ti-Lao, Choshun River			39
22/09/1999	E Asia	Japan				2
07/10/1999	C. America	Mexico	**Teziutlan**, Puebla	19.8167	-97.3500	341
24/10/1999	S Asia	Nepal				10
08/11/1999	S. America	Peru	**Sicsi**	-13.0333	-75.9500	40
09/12/1999	SE Asia	Indonesia	Dberang Pallinggam (Sumatra)			56
15/12/1999	S. America	Venezuela	**Vargas**	10.0889	-67.0961	30000
17/12/1999	Europe	Italy				4
25/12/1999	S. America	Colombia	Narino			22
		36 landslides	3 multiple landslide events			30995
10/02/2000	Europe	Bosnia-Herzegovina	**Velika Broda** (Zenica)	44.1953	17.8786	6
23/02/2000	SE Asia	Indonesia	**Brebes** District (Java Island)	-7.1114	110.6892	70
18/03/2000	S America	Peru	**Uralla**, 190 miles S Lima	-13.0000	-74.3833	22
12/04/2000	S. America	Ecuador	**Quito**	-0.2167	-78.5000	14
19/04/2000	S America	Guyana	Remire-Montjoly			10
01/06/2000	S. Asia	India	**Moradabad**, Bijnore districts (Uttar Pradesh), Garhwal Himalayan re	28.8333	78.7833	43
05/06/2000	E. Asia	China P Rep	Sichuan, Guizhou provinces			71
10/06/2000	E. Asia	China P Rep	Zamulongba River Valley, SE Tibet			94
24/06/2000	S. Asia	Bangladesh	**Chittagong** University	22.3636	91.8033	10
27/06/2000	C. America	Costa Rica	Miramar de Puntarenas (San Jose), 120km NW **San Jose**	9.9333	-84.0833	9
04/07/2000	C. Africa	Ethiopia	**Ofa** district (North Omo)	7.4167	36.2667	4
10/07/2000	SE Asia	Philippines	**Manila**	14.6042	120.9822	287
12/07/2000	S. Asia	India	**Ghatkopar** (Bombay)	19.0833	72.9000	98
19/07/2000	C. Asia	Russia	Tymauz (Kabardino-Balkaria region, Caucasus)			7
22/07/2000	SE Asia	Viet Nam	**Ban Sai** (Sapa region, Lao Cai province),	22.3000	103.9833	33
01/08/2000	S. America	Brazil	Alagoas, Pernambouc, Recife, **Sergipe**	-21.1333	-50.8000	60
11/08/2000	S. Asia	India	Himalayan foothills			86
13/08/2000	E. Asia	China P Rep	Yingjiang county (Yunnan province)			14
16/09/2000	S. America	Peru	**Arma** (Cusco department)	-13.2167	-73.0667	11
23/09/2000	Africa	Nigeria	Amakor (Anambra state)			17
03/10/2000	SE Asia	Viet Nam	**Sin Ho** district (Lai Chau province)	22.3667	103.2333	40
09/10/2000	Africa	Angola	Chassuala (near **Saurimo**, Lunda-Sul province)	-9.6500	20.4000	13
13/10/2000	Europe	Switzerland	**Gondo** (Valais)	46.2000	8.1333	16
14/10/2000	S. America	Ecuador	**Penipe** (Chimborazo province)	-1.5667	-78.5333	30

Date	Continent	Country	Location	Latitude	Longitude	Fatalities
14/10/2000	S. America	Ecuador	**Guano** (Chimborazo province)	-1.5833	-78.6333	
31/10/2000	SE Asia	Indonesia	**Cilacap**, Banyumas (Central Java)	-7.7333	109.0000	40
05/11/2000	SE Asia	Indonesia	**Purbalingga**	-7.4000	109.3667	52
05/11/2000	SE Asia	Indonesia	**Kebumen**	-7.3667	109.2167	
08/11/2000	SE Asia	Philippines				11
10/11/2000	SE Asia	Philippines	**Cabugao**-Apayao (Kaling-Apayao province)	17.4500	121.2167	11
20/12/2000	Africa	Nigeria	Atakumosa (Osun state)			15
		27 landslides	3 multiple landslide events			1194
02/01/2001	Europe	UK	**Nefyn**, Lleyn Peninsula	52.9333	-4.5000	1
13/01/2001	C. America	El Salvador	**Santa Tecla** (Las Colinas)	13.6769	-89.2797	518
22/01/2001	SE Asia	Indonesia	North Sulawesi province			63
22/01/2001	Africa	Tanzania	Kigoma region			13
25/01/2001	S. America	Bolivia	**La Paz**	-16.5000	-68.1500	4
11/02/2001	SE Asia	Indonesia	**Cipanas**, Lebak district (West Java province)	-6.5422	106.3839	122
13/02/2001	C. America	El Salvador	Chichontepec Volcano, nr **San Vicente**	13.6333	-88.8000	39
05-06/03/2001	Europe	Portugal	Sao Vicente Valley, Madeira	32.8000	-17.0500	5
17/04/2001	Africa	Angola	**Boavista** District	-8.6058	13.5614	8
28/04/2001	S. America	Colombia	Choco department			7
01/05/2001	E Asia	China P Rep	**Wulong** (Chongqing municipality)	29.3333	107.7167	74
01/05/2001	Africa	Uganda	**Kasese** District	0.2300	29.9883	1
03/05/2001	SE Asia	Thailand	Phrae and Sukothai Provinces			83
20/05/2001	C. Asia	Tajikistan	Varzob region			1
27/05/2001	E Asia	China P Rep	Dongdongyan, **Goujia** Township of southwestern China's Sichuan P	28.2858	108.3408	8
01/06/2001	S. Asia	Nepal	**Janakpur**	28.7333	80.9333	144
01/06/2001	S. Asia	Nepal	**Lumbini**	27.4833	83.2833	
05/06/2001	S America	Colombia	**La Fea** (Antioquia province)	7.2878	-75.3944	14
08/06/2001	SE Asia	Indonesia	Tajur Halang village, approximately 20 miles south of **Jakarta**	-6.1397	106.8269	4
11/06/2001	S America	Ecuador				30
12/06/2001	S America	Ecuador	**Papallacta**	-0.3667	-78.1333	6
26/06/2001	E Asia	China P Rep	**Hangzhou**	30.2553	120.1689	22
29/06/2001	S Asia	Nepal	Statdevi, **Dhading**	27.8667	84.9167	28
02/07/2001	E Asia	China P Rep	**Yinmin** Town. Yunnan	26.3000	103.0000	19
02/07/2001	E Asia	China P Rep	Jinping county			15
02/07/2001	S America	Colombia	La Fea, **Puerto Valdivia**, Antioquia	7.2878	-75.3944	4
02/07/2001	S America	Colombia	La Fea, **Puerto Valdivia**, Antioquia	7.2878	-75.3944	4

Date	Continent	Country	Location	Latitude	Longitude	Fatalities
04/07/2001	SE Asia	Philippines				6
04/07/2001	SE Asia	Philippines	**Baguio City**	16.4164	120.5931	34
10/07/2001	S Asia	Pakistan	**Chitta Katha Baihk**, Kaghan valley	34.9417	74.4875	15
16/07/2001	S Asia	India	**Rudraprayag** district (Uttaranchal state)	30.2833	78.9833	27
22/07/2001	S Asia	Nepal	**Tikapur**, Myadi, W Nepal	28.5000	81.1333	20
28/07/2001	E Asia	China P Rep	**Ya'an** City, Sichuan	29.9833	103.0833	5
28/07/2001	E Asia	China P Rep	Zhenyuan county (Yunnan province), 200km SW **Kunming**	25.0389	102.7183	16
31/07/2001	E Asia	Taiwan	Country-wide			240
14/08/2001	S Asia	India	**Chamba** district (Himachal Pradesh)	32.5667	76.1337	16
25/09/2001	E Asia	China P Rep	**Mingshan** county (Sichuan province)	30.1333	103.1667	11
28/09/2001	E Asia	China P Rep	**Yongsheng** county (Yunnan province)	26.7000	100.7500	14
28/10/2001	S America	Peru	**Jachanuanca** (South-East)	-10.8000	-75.3333	20
09/11/2001	S Asia	India	Amboori village, near **Trivandrum** (Kerala province)	8.4833	76.9167	55
10/11/2001	Europe	Turkey	**Camlihemsin** (Rize province)	41.0303	41.0944	9
10/11/2001	Europe	Turkey	**Cayeli** (Rize province)	41.0894	40.7306	
10/11/2001	Europe	Turkey	**Ardesen** (Rize province)	41.1911	40.9875	
10/11/2001	Europe	Turkey	**Hemsin** (Rize province)	41.0333	40.8833	
10/11/2001	Europe	Turkey	**Pazar** (Rize province)	41.1792	40.8842	
10/11/2001	Europe	Turkey	**Findikli** (Rize province)	41.2744	41.1508	
22/11/2001	S America	Colombia	**Filadelfia**, Departmento de Caldas	5.3078	-75.5636	47
25/12/2001	Africa	Zaire/Congo Dem Re	Nord-Kivu province			12
		31 landslides	11 multiple landslide events			1784
05/01/2002	SE Asia	Indonesia	Isolated island off Sulawesi			4
05/01/2002	SE Asia	Indonesia	Isolated island off Sulawesi			
18/01/2002	SE Asia	Indonesia	S Sumatra			18
28/01/2002	SE Asia	Malaysia	**Simunjan** district (Borneo Isl.)	1.3833	110.7500	10
29/01/2002	SE Asia	Indonesia	**Jakarta** and elsewhere	-6.1744	106.8294	42
05/02/2002	S America	Peru	**Lima**	-12.0500	-77.0500	2
09/02/2002	Africa	DR Congo	"east"			40
16/02/2002	SE Asia	Indonesia	**Semarang**, Central Java	-7.0114	110.4111	7
02/04/2002	Australasia	Papua New Guinea	**Wantoat** (Markham district, Morobe province)	-6.1333	146.4833	36
03/04/2002	S Asia	Afghanistan	Surkundara Valley, Samanghan Province (65km from **Feyzabad**)	37.1175	70.5797	150
08/04/2002	SE Asia	Indonesia	**Bojonggenteng** village, Sukabumi district, West Java	-7.2833	106.6167	3
12/04/2002	SE Asia	Indonesia	**Semarang**, Central Java	-7.0114	110.4111	4
24/04/2002	C Asia	Tajikistan	Northern'			5

Date	Continent	Country	Location	Latitude	Longitude	Fatalities
30/04/2002	Africa	Kenya	**Meru**, Muranga's districts	0.0500	37.6500	16
14/06/2002	E Asia	China P Rep	**Chongqing**	29.5628	106.5528	10
01/07/2002	E Asia	China P Rep	Fujian Province			10
01/07/2002	Australasia	Micronesia	Chuuk State			40
07/07/2002	SE Asia	Philippines	**Batangas**	13.7594	121.0600	4
07/07/2002	SE Asia	Philippines	**Olongapo** City	14.8292	120.2828	3
16/07/2002	S America	Ecuador	Mendez region (170km SE **Quito**)	-0.2167	-78.5000	60
15-24/07/2002	S Asia	Nepal	Makwanpur, Khotang, Kathmandu, Chitwan, Kavre, Dhanusha, Mahottari, Bhojpur, Dhankutta, S			472
26/07/2002	E Asia	China P Rep	Yunnan			17
01/08/2002	E Asia	China P Rep	(northern) Yunnan province			29
07/08/2002	C Asia	Tajikistan	**Dasht** village, Roshtkala district of Gorno-Badakhshan	37.7667	71.5333	24
07/08/2002	C Asia	Tajikistan	**Langar** villages, Roshtkala district of Gorno-Badakhshan	37.0517	72.6728	
07/08/2002	S Asia	India	Kurla near Mumbai	18.7500	77.1333	6
08/08/2002	S Asia	Nepal	Tapeljung			30
09/08/2002	N America	USA	Nuuanu, Hawaii			1
11/08/2002	S Asia	India	Bihar, Assam, Manipur, Uttranchal			33
13/08/2004	E Asia	China P Rep	SW China'			7
14/08/2002	E Asia	China P Rep	Xinping county, Yunnan province (200km S **Kunming**)	25.0389	102.7183	67
21/08/2002	S Asia	Nepal	Ramechap			41
22/08/2002	S Asia	Nepal	Across Nepal			46
03/09/2002	SE Asia	Thailand	Ban Tha Sala (Mae Hong Son)	19.2667	97.9333	39
13/09/2002	C America	Guatemala	El Porvenir (100 miles W Guatemala City)	14.7667	-89.7667	52
15/09/2002	E Asia	China	Hubei (south of **Kunming**)	25.0389	102.7183	22
18/09/2002	E Asia	China	Shenzhen			30
21/09/2002	C. Asia	Russia	Nizhny Karmadon, N. Ossetia (940 miles SE **Moscow**)	55.7522	37.6156	136
24/09/2002	Caribbean	Barbados	Mount Grenan			4
02/10/2002	M. East	Syria	Aleppo	36.2028	37.1586	80
05/10/2002	S. Asia	Sri Lanka	Henagahathi Ella, **Belihul Oya**	6.7167	80.7667	8
05/10/2002	E Asia	China	Yichikou, Wuding County, Yunnan Province (2250km SW Beijing)			15
31/10/2002	S Asia	Pakistan	Karakoram Highway			2
01/11/2002	S. America	Columbia	Montecristo, San Lucas Mountains			66
01/11/2002	S Asia	India	Gilgit-Astore region (P.O.K.)			1
20/11/2002	SE Asia	Malaysia	Hillview Garden Suburd, **KL**	3.1667	101.7000	8
28/11/2002	Europe	Italy	**Brescia**	45.5500	10.2500	1
08/12/2002	E. Asia	China	**Qujing**, Yunnan Province	25.4833	103.7833	8

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10/12/2002	S America	Brazil	Nr **Rio** on Coast	-22.9000	-43.2333	37
11/12/2002	SE Asia	Indonesia	**Pacet**, E.Java	-7.6667	112.5333	126
27/12/2002	SE Asia	Indonesia	**Gunungkemala**, Sumatra	-3.4000	104.1667	10
27/12/2002	SE Asia	Indonesia	**Mambi**, Polewali Mamasa, S Sulewesi	-2.9519	119.1769	2
		44 landslides	8 multiple landslide events			1884
11/01/2003	S America	Brazil	**Rio de Janeiro**	-22.9000	-43.2333	29
11/01/2003	SE Asia	Indonesia	Borneo			10
17/01/2003	S America	Brazil	**Minas Gerais**	-8.9667	-72.7833	45
22/01/2003	Caribbean	Bermuda	Bermuda College, **Paget**	32.2836	-64.7706	1
24/01/2003	E. Asia	China	**Sanya**, Hainan	19.2639	109.6700	6
29/01/2003	SE. Asia	Indonesia	**Garut**, Kuningan, West Java	-6.7850	107.2856	22
31/01/2003	SE. Asia	Indonesia	**Cantilan**, Kuningan, West Java	-7.1000	108.4333	10
18/02/2003	Europe	Greece	**Roussospition**, Crete	35.3333	24.5000	1
19/02/2003	S. Asia	Pakistan	Dasu, near **Kohistan**	25.1667	68.1667	9
19/02/2003	N. America	Bermuda	Elbow Beach Hotel, **Hamilton**	32.2942	-64.7839	1
04/03/2003	C. America	Mexico	**Tijuana**	25.2500	-111.1333	1
04/03/2003	S. Asia	Pakistan	Neelum Valley			2
04/03/2003	S. Asia	Pakistan	**Tolti**, Skardu	35.0333	76.1000	1
06/03/2003	S. Asia	India	**Doda** District, Jammu	33.1333	75.5667	1
13/03/2003	SE. Asia	Philippines	Mt Diwalwal, **Monkayo**, Compostela Valley	7.8153	126.0544	2
19/03/2003	S. America	Colombia	**Manizales**, Caldas regions	5.0700	-75.2506	26
24/03/2003	E Asia	Japan	**Hanayama**, Miyagi	38.4500	140.4500	1
31/03/2003	S. America	Bolivia	Chima, nr **Tipuani**	-15.5500	-68.0000	117
02/04/2003	E Asia	China	**Yangjiapinglinchang**, Badong County, Hubei	39.9725	115.3794	4
05/04/2003	SE Asia	Indonesia	Flores			76
10/04/2003	E Asia	China	Dashangou Village, **Wude Town**, Zhenxiong County, Yunnan	27.5667	104.7000	8
20/04/2003	C. Asia	Kyrgyzstan	Kara Taryk village, **Uzgen** Dirstrict, Osh	40.7667	73.3000	38
24/04/2003	C. America	Guatemala	**Chichicaste**	14.8833	-90.2167	23
25/04/2003	E Asia	China	**Ili River Valley**, Gongliu County, Xinjiang	43.9569	80.8503	8
30/04/2003	S America	Ecuador	**El Pongo**, Catopaxi	-0.7000	-78.8000	9
30/04/2003	Africa	Kenya	Kapkisei Village, **Kericho**	-0.4000	37.0167	4
May-03	S Asia	Sri Lanka				266
02/05/2003	Australasia	Papua New Guinea	Tokia, South Karoba			13
02/05/2003	S Asia	Pakistan	Kajo Bela, **Kohistan**	25.1667	68.1667	14
04/05/2003	S Asia	India	Bawngkawn			2

Date	Continent	Country	Location	Latitude	Longitude	Fatalities
05/05/2003	S Asia	Bangladesh	**Noabad**, Akhaura	24.4333	90.8833	31
05/05/2003	S Asia	India	**Lawngtlai**	22.5333	92.9000	1
11/05/2003	E Asia	China	Miao-Dong, Ghuizou			33
15/05/2003	Africa	Kenya	Gatara Village, **Murang'a** District, Central Province	-0.7167	37.1500	1
16/05/2003	Africa	Uganda	**Mbarara**	-0.6583	30.6758	30
17/05/2003	S. Asia	Sri Lanka	Dothupitiya (25km E **Ratnapura**)	6.6828	80.3992	25
17/05/2003	E Asia	China	Xiangjiang River, Hunan			38
24/05/2003	Pacific Island	American Samoa				6
01/06/2003	E Asia	China	Sichuan			2
05/06/2003	E Asia	China	**Ili** River Valley, Xinjiang Uygur	43.9569	80.8503	26
05/06/2003	SE Asia	Philippines	Tres Marias, Sorsogan Province nr **Donsol town**	12.9083	123.5981	5
05/06/2003	C. America	Mexico	**Veracruz**	20.2597	-99.1389	5
10/06/2003	E Asia	China	**Ankang City**, Shangxi Province	32.6800	109.0172	9
12/06/2003	S Asia	Nepal	Fungwa Village, Niguradin, Fungling, **Tapeljung**	27.3500	87.6667	6
15/06/2003	S Asia	Bangladesh	**Cox's Bazaar**	21.4333	91.9833	6
17/06/2003	SE Asia	Philippines	Sitio Macalapi, **Leyte**	11.3703	124.4889	3
17/06/2003	SE Asia	Philippines	Samar			1
19/06/2003	SE Asia	Philippines	**Tuba**, Benguet	12.9167	123.6000	2
20/06/2003	S Asia	India	Milan Nagar, **Ghatkopar**	19.0833	72.9000	1
20/06/2003	E Asia	China	Azuigou village, Wudaoqing township, **Puje**, Sichuan	27.3933	102.5611	10
20/06/2003	S Asia	Nepal	Majjhi Goan, Myagdhi			3
22/06/2003	S Asia	India	Vaibhyavadi (300 miles south of Bombay, **Rajapur**)	20.1667	74.6333	52
24/06/2003	E Asia	China	**Zhuxi** county, Hubei	32.3103	109.7047	6
24/06/2003	S Asia	India	Uttara Kanada, Karnataka			2
25/06/1905	C Asia	Kyrgyzstan	Nationwide			15
25/06/2003	E Asia	China	Xishui, Guizhou	28.3375	106.2214	24
25/06/2003	E Asia	China	Hubei			7
25/06/2003	E Asia	China	Heijuan, Sichuan			4
26/06/2003	S Asia	Bangladesh	Throughout Bangladesh			65
28/06/2003	S Asia	Afghanistan	Aseef, Ragh, Badakhstan			3
28/06/2003	S Asia	Nepal	Across Nepal			7
28/06/2003	S Asia	Nepal	Saune, **Udaipur**	26.9333	86.5167	6
28/06/2003	S Asia	India	**Bilonia**, S Tripura	24.7000	77.3333	1
29/06/2003	S Asia	Bangladesh	**Patiya**, S. Bangladesh	22.3031	91.9783	4
29/06/2003	S Asia	Nepal	Taksindhu, Solukhumbu			4

Date	Continent	Country	Location	Latitude	Longitude	Fatalities
30/06/2003	SE Asia	Vietnam	**Lai Chau**	22.0667	103.1667	1
30/06/2003	S Asia	India	**Shillong**, Meghalaya	25.5667	91.8833	2
/07/2003	E Asia	China	**Chongqing**, SW China	29.5628	106.5528	28
/07/2003	S Asia	India	North and West Bengal			24
03/07/2003	Africa	Uganda	**Buwabala**, Mbale District	0.9064	34.3619	4
06/07/2003	S Asia	India	**Mussoorie**	30.4500	78.0833	1
08/07/2003	S Asia	India	**Dudhia-Gujarat**, Mirik	22.8833	74.0000	25
08/07/2003	S Asia	Nepal	**Tapeljung**	27.3500	87.6667	1
08/07/2003	S Asia	Pakistan	Gulistan-e-Jauhar, **Karachi**	24.8667	67.0500	8
09/07/2003	E Asia	China	Yongshun, Hunan	29.3606	111.1814	26
09/07/2003	S Asia	Tibet	Selila Mountain			16
10/07/2003	E Asia	China	Anhui			12
11/07/2003	S Asia	Nepal	Janushivpur (100 miles W **Kathmandu**)	27.7167	85.3167	3
12/07/2003	E Asia	China	**Danba** County, Sichuan	30.9500	101.9167	51
13/07/2003	E Asia	China	Qianjiangping, **Shazhenxi** township, Hubei	30.9833	110.6167	24
13/07/2003	E Asia	China	**Fengjie**, Chongqing	31.0500	109.5167	6
15/07/2003	S Asia	Nepal	Ikhabu NE Nepal)			67
16/07/2003	E Asia	China	**Guangyuan** City, Sichuan	32.4403	105.8214	11
16/07/2003	Australasia	Papua New Guinea	Ok Tedi			1
17/07/2003	SE Asia	Philippines	**Donsol** Town, Sorsogon, Bicol	12.9083	123.5981	5
17/07/2003	C. America	Mexico	**Santa Maria Chilchotla**, Oaxaca	18.2333	-96.8167	9
17/07/2003	SE Asia	Philippines	**Tubo**, Benguet	16.8514	120.7928	2
18/07/2003	S Asia	India	Antop Hill, Mumbas			2
19/07/2003	S Asia	India	**Ganga Ravapalli**, Arunachal Pradesh	16.9500	77.4667	2
19/07/2003	E Asia	Japan	Fukagawa, **Minamata**	32.2167	130.4000	4
19/07/2003	E Asia	Japan	Hogawachi, **Minamata**	32.2167	130.4000	23
19/07/2003	E Asia	China	**Chongqing**	29.5628	106.5528	7
20/07/2003	Africa	Nigeria	Upke Ward, Bayutung, Cross River State			6
21/07/2003	Africa	Cameroon	Magha, Wabane, SW Cameroon (400km from **Yaounde**)	3.8667	11.5167	21
21/07/2003	E Asia	Japan	Hishikari, **Kagoshima**	31.6000	130.5500	2
24/07/2003	E Asia	China	**Maoming**, Guandong	21.6500	110.9000	1
25/07/2003	S Asia	India	Shanti Nagar near **Jeory**, Himachal Pradesh	31.2489	77.0944	2
25/07/2003	SE Asia	Vietnam	**Lai Chau**	22.0667	103.1667	5
26/07/2003	S Asia	India	**Guwahati**, Assam	26.2500	91.7500	1
26/07/2003	S Asia	India	Hudan, Chambi District			3

Date	Continent	Country	Location	Latitude	Longitude	Fatalities
27/07/2003	S Asia	Nepal	Aglung, **Gulmi**, W Nepal	28.0667	83.2500	5
28/07/2003	Africa	Nigeria	Mambilla Plateau, Taraba			7
30/07/2003	S Asia	Nepal	Kabilas Village, Chitwan (nr **Kathmandu**)	27.7167	85.3167	20
30/07/2003	S Asia	Nepal	Koteswora Village (60 m W **Kathmandu**)	27.7167	85.3167	4
30/07/2003	S Asia	Nepal	Jalbire Village, Chitwan (nr **Kathmandu**)	27.7167	85.3167	4
30/07/2003	E Asia	China	Lintan County			6
30/07/2003	S Asia	Afghanistan	Panjshir Valley			30
30/07/2003	S Asia	Bangladesh	**Cox's Bazaar**	21.4333	91.9833	6
31/07/2003	S Asia	India	Baijnath, Kangra Valley			5
31/07/2003	S Asia	Nepal	Chhip Chhipe, **Tanahun**	28.0333	84.3333	6
31/07/2003	S Asia	Nepal	**Rupendehi**	27.4833	83.2833	1
31/07/2003	S Asia	Nepal	Nr **Kalaiya**, Bara District	27.0333	85.0000	1
31/07/2003	S Asia	Nepal	**Siraha**	26.6500	86.2000	1
31/07/2003	S Asia	Nepal	Krishna Bhir, **Dhading**	27.8667	84.9167	2
31/07/2003	S Asia	Nepal	Gaidakot, Nawaparasi District (**Parasi**)	27.5333	83.6667	1
31/07/2003	S Asia	Nepal	Ratanpur, Nawaparasi District (**Parasi**)	27.5333	83.6667	2
31/07/2003	S Asia	Nepal	Bhagar Village, Devchuli, Nawaparasi District (**Parasi**)	27.5333	83.6667	7
31/07/2003	S Asia	Nepal	Damauli, **Tanahun**	28.0333	84.3333	6
31/07/2003	S Asia	Nepal	Hadikhola, **Makwanpur Garhi**	27.4167	85.1333	7
31/07/2003	S Asia	Nepal	Manakamana Village, **Gorkha**	28.0000	84.6333	23
31/07/2003	S Asia	Nepal	Manakamana Village, **Gorkha**	28.0000	84.6333	
31/07/2003	S Asia	Nepal	Manakamana Village, **Gorkha**	28.0000	84.6333	
31/07/2003	S Asia	Nepal	Manakamana Village, **Gorkha**	28.0000	84.6333	
31/07/2003	S Asia	Nepal	Manakamana Village, **Gorkha**	28.0000	84.6333	
01/08/2003	S Asia	India	Chamera Reservoir, Chamba Valley			2
02/08/2003	S Asia	India	**Mandi**	31.7500	76.9167	1
02/08/2003	S Asia	India	**Dharamsala**	32.2500	76.3333	1
06/08/2003	Africa	Nigeria	Taraba State			7
07/08/2003	S Asia	Nepal	Surumkhim,**Taplejung**, NE Nepal	27.3500	87.6667	7
07/08/2003	E Asia	China	**Sucheng** village, Ningxian County, Gansu	34.1464	105.5983	4
08/08/2003	E Asia	Japan	Shikoku			2
09/08/2003	E Asia	China	**Xiangyan** township, Mianyang City, Sichuan	32.1072	104.7772	4
09/08/2003	E Asia	China	Xiazhuang Village, **Wenchuan** County Sichuan	31.4667	103.5833	1
15/08/2003	S Asia	Nepal	Gebung, Ramche, Rasuwa			5
15/08/2003	S Asia	Nepal	Ramche, **Rasuwa**	27.0800	86.4333	20

Date	Continent	Country	Location	Latitude	Longitude	Fatalities
15/08/2003	S Asia	Nepal	Namarjung, **Kaski**	28.2667	83.8833	5
16/08/2003	N America	USA	**Georgetown** Hill, Denver (Colorado State)	39.7061	-105.6969	1
17/08/2003	Africa	Ethiopia	Tekezze River, N. Ethiopia			6
19/08/2003	S Asia	Nepal	**Palpa**	27.8667	83.4833	1
19/08/2003	S Asia	Nepal	Khatiwada, **Doti**	29.2667	80.9833	2
19/08/2003	S Asia	Nepal	Bajkaresi Village, Gulmi District (**Tamghas**)	28.0667	83.2500	5
20/08/2003	E Asia	China	Kyegudo, Yushu Province			1
20/08/2003	S Asia	India	Mission Veng, **Aizawl**	23.7333	92.7167	3
22/08/2003	S Asia	Nepal	Parchey, Siklesh, **Kaski**	28.2667	83.8833	3
23/08/2003	Africa	Uganda	Kabeyi, **Kapchorwa**	1.3828	34.5244	2
26/08/2003	Africa	Ethiopia	Detta Woreda, Gamo Gaffo, S. Ethipia			11
26/08/2003	S Asia	Nepal	Duduwa, **Ramechhap**	27.3333	86.0833	3
26/08/2003	E Asia	China	Ya'an City, Sichuan	29.9833	103.0833	19
26/08/2003	E Asia	China	Ya'an City, Sichuan	29.9833	103.0833	
27/08/2003	S Asia	Nepal	Daudha, **Doti**	29.2667	80.9833	1
27/08/2003	S Asia	Nepal	Bajhak Kani, **Doti**	29.2667	80.9833	1
28/08/2003	E Asia	China	Baoji County, Shaanxi Province			13
28/08/2003	E Asia	China	Baoji County, Shaanxi Province			
29/08/2003	Europe	Italy	Val Canale, Udinese			2
01/09/2003	SE Asia	Vietnam	Sa Mao Pho village, **Bac Ha** district, northern Lao Cai province	22.5500	104.2667	3
02/09/2003	E Asia	China	Shaanxi Province and Hubei Province			3
03/09/2003	S Asia	Nepal	Andheri Khola in Baseri VDC-7, **Dhading**	27.8667	84.9167	5
12/09/2003	Europe	Bulgaria	**Balchik**	43.4167	28.1667	2
12/09/2003	E Asia	South Korea	?			12
12/09/2003	E Asia	South Korea	**Yeosu** city	34.7500	127.7500	1
14/09/2003	SE Asia	Indonesia	**Mangunjaya** village, Bandung, Java	-7.5000	108.6833	5
20/09/2003	S Asia	Nepal	**Tehrathum**	27.1167	87.5333	2
20/09/2003	SE Asia	Indonesia	Lengkong hamlet, Pasir Buncir village, **Caringin** subdistrict	-6.2833	106.2333	5
23/09/2003	E Asia	China	Liangjiagou, Shaanxi province			12
26/09/2003	N America	USA	**Georgetown**, Denver, Colorado State	39.7061	-105.6969	1
28/09/2003	S E Asia	Philippines	**Antipolo** City, Rizal province	14.5864	121.1753	1
01/10/2003	S Asia	Sri Lanka	**Kudagala**	6.2833	80.1667	1
01/10/2003	S Asia	Sri Lanka	**Elpitiya**	7.0167	79.9000	2
01/10/2003	S Asia	Sri Lanka	**Yakkalamulla**	6.1000	80.3500	8
01/10/2003	S Asia	India	Wadarpada, **Kandivalli**	11.1167	76.8000	2

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01/10/2003	S Asia	India	**Malad**, N. Mumbai	19.1833	72.8333	3
02/10/2003	SE Asia	Malaysia	**Ringlet**, Cameron Highlands	4.4167	101.3833	1
05/10/2003	SE Asia	Indonesia	Tanjung Jabung Bar, **Jambi**, Sumatra	-1.6000	103.6167	5
06/10/2003	Caribbean	Haiti	**Port-au-Prince**	18.5392	-72.3350	13
06/10/2003	Caribbean	Haiti	**Port-au-Prince**	18.5392	-72.3350	
06/10/2003	Caribbean	Haiti	**Port-au-Prince**	18.5392	-72.3350	
06/10/2003	Caribbean	Haiti	**Port-au-Prince**	18.5392	-72.3350	
06/10/2003	SE Asia	Malaysia	Bukit Besar, Kulim	5.9500	100.4167	2
07/10/2003	S Asia	India	Vetaltekdi hill, near Chatuhshrungi, **Pune**	18.5333	73.8667	4
07/10/2003	C. America	El Salvador	Highway in Central El Salvadore			1
09/10/2003	SE Asia	Indonesia	**Dawuhan** village, Trenggalek district, East Java	-8.1922	112.7431	2
09/10/2003	SE Asia	Indonesia	Grasberg Mine, W Papua			8
10/10/2003	S Asia	India	Likhuvir, Kalimpong sub-division			1
14/10/2003	SE Asia	Malaysia	Jalan Gunung Raya, **Langkawi**	6.3167	99.8500	1
16/10/2003	SE Asia	Vietnam	**Quang Nam**	15.8858	108.2569	1
16/10/2003	S America	Brazil	Vila Cruzeiro slum, **Rio**	-22.9000	-43.2333	5
17/10/2003	SE Asia	Indonesia	Semangkung village, Pejawaran district, **Banjarnegara**	-7.3833	109.6833	1
18/10/2003	SE Asia	Indonesia	**Banyumudal** village, Wonosobo district, Central Java	-7.4000	110.0167	2
02/11/2003	SE Asia	Indonesia	Bukit Lawang,Banghorak subdistrict, **langka** district, N. Sumatra	4.0500	96.2333	244
03/11/2003	SE Asia	Indonesia	Muatan Batu area, Tumbang Titi subdistrict, Ketapang regency, Wes	1.6167	109.1833	8
10/11/2003	E Asia	S Korea	**Namyangju**, Gyeonggi Province	37.6367	127.2142	2
11/11/2003	E Asia	China	**Xingren** county, Guizhou province	26.3333	107.8167	11
11/11/2003	E Asia	China	**Xingren** county, Guizhou province	26.3333	107.8167	
11/11/2003	E Asia	China	**Xingren** county, Guizhou province	26.3333	107.8167	
13/11/2003	SE Asia	Vietnam	**Quang Nam**	15.8858	108.2569	19
13/11/2003	E Asia	China	**Fugu** County, Shaanxi province	39.0261	111.0556	12
17/11/2003	Caribbean	Dominican Republic	**Monte Cristi**	19.8667	-71.6500	1
21/11/2003	SE Asia	Indonesia	Cukang village, **Cikajang** sub-district, Garut district, West Java	-7.3667	107.7833	1
26/11/2003	Africa	Democratic Republic	**Matadi**	-4.6833	17.3167	11
03/12/2003	S. America	Colombia	**Mistrato**, Risaralda province	5.2994	-75.8875	7
07/12/2003	SE Asia	Indonesia	Pergodangan, Central **Tapanuli**, N. Sumatra	2.8500	98.2667	1
11/12/2003	N America	USA	**Maggie Valley**, Haywood County, Georgia	35.5181	-83.0978	1
14/12/2003	E Asia	China	**Wangmo** county, Guizhou province	25.1667	106.1000	10
15/12/2003	SE Asia	Indonesia	Putada village, **Majene** district, S. Sulawesi	-3.5464	118.9600	4
19/12/2003	SE Asia	Philippines	Mt. Diwata (commonly known as Diwalwal), **Monkayo**, Compostela	7.8153	126.0544	1

Date	Continent	Country	Location	Latitude	Longitude	Fatalities
19/12/2003	SE Asia	Philippines	Mt. Diwata (commonly known as Diwalwal), **Monkayo**, Compostela	7.8153	126.0544	
19/12/2003	SE Asia	Philippines	**T'boli**, South Cotabato	6.2000	124.8330	1
19/12/2003	SE Asia	Philippines	Islands of Leyte, Panaon and Bohol as well as the northeast section of Minda			154
21/12/2003	SE Asia	Indonesia	Donggala district, Central Sulawesi			2
25/12/2003	N America	USA	**San Bernadino**, Ca	34.1083	-117.2889	2
25/12/2003	N America	USA	Saint Sophia Camp, **San Bernadino**, Ca	34.1083	-117.2889	16
04-12/02/03	SE Asia	Brunei	Sarawak			1
14-28/01/03	SE Asia	Indonesia	various			35
		197 landslides	16 multiple landslide events			2536
02/01/2004	S Asia	Pakistan	Shogran, 40km from **Chitral**, N W Frontier Province	35.8419	71.7819	3
02/01/2004	Africa	Mozambique	Tsiquiri region, Sofala province			6
03/01/2004	E Asia	China	Jingpo Village, **Linfen City**, Shanxi, N. China	36.0889	111.5189	14
04/01/2004	SE Asia	Indonesia	Wanahayu village, **Maja** subdistrict, Majalengka district, West Java	-6.9000	108.2833	4
11/01/2004	C America	Mexico	**Pichucalco**, c.80 kms north of Tuxtla Gutierrez, Chiapas state, SW	17.5167	-93.0667	2
15/01/2004	S America	Brazil	**Xerem**, Rio	-22.5856	-43.2950	3
14/01/2004	SE Asia	Malaysia	Bau district, Birneo	1.4167	110.1500	1
29/01/2004	SE Asia	Indonesia	**Purworejo** regency, in Central Java	-7.4742	110.2833	15
02/02/2004	S Asia	India	Jammu-Srinagar national highway km 158 between Bannihal and **Ra**	33.2500	75.2500	1
02/02/2004	S Asia	India	Jammu-Srinagar national highway km 147 between **Bannihal** and R	33.4167	75.4167	1
09/02/2004	S Asia	Pakistan	Tehsil Khawaza Khela, Swat district, N Pakistan - **Saidu sharif (capi**	34.7500	72.3500	5
14/02/2004	S Asia	Pakistan	**Batgram**, N Pakistan	34.6833	73.0167	13
16/02/2004	SE Asia	Malaysia	**Mambang Diawan**, Kampar	4.2667	101.1500	1
22/02/2004	Australasia	Australia	**Avalon** Beach	-33.6333	151.3333	1
26/02/2004	Pacific Island	Vanuatu	Malekula			1
06/03/2004	S America	Colombia	**Medellin**	16.4500	167.3000	2
07/03/2004	Europe	Turkey	**Artvin** province, E Turkey	41.1822	41.8194	1
11/03/2004	S Asia	India	**Kalal** border area, Rajouri district, Kashmir	33.0833	74.2306	4
13/03/2004	Europe	Italy	**Bormio**	46.4667	10.3667	1
14/03/2004	C Asia	Kazakhstan	**Taldy-Bulak**, Talgar district (20km E of Almaty)	43.3333	75.2833	29
16/03/2004	SE Asia	Vietnam	Sapa town, **Lao Cai**	22.4833	103.9500	3
26/03/2004	SE Asia	Indonesia	**Lengkese** (Menimbohoi subdistrict), Mount Bawakaraeng, Gowa Re	5.4833	119.4500	33
26/03/2004	SE Asia	Indonesia	**Panaikang**, (Menimbohoi subdistrict), Mount Bawakaraeng, Gowa R	-5.5447	119.9103	
01/04/2004	Middle East	Saudi Arabia				30
08/04/2004	Pacific Island	Fiji	Wainibuka River, Viti Levu (north of capital **Suva**)	-18.1333	178.4167	6
08/04/2004	E Asia	China	Mohuer Township, **Gongliu** County, Xinjiang Uygur Autonomous Re	43.4667	82.1489	8

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10/04/2004	S Asia	Pakistan	**Bangla**, Karakoram Highway	29.7792	69.4333	2
10/04/2004	S. America	Peru	Aguas Calientes, nr **Macchu Pichu**	-13.1583	-72.5314	11
13/04/2004	N America	USA	**McKeesport**, Pittsburgh, Pennsylvania	40.3478	-79.8644	1
17/04/2004	C Asia	Kyrgyzstan	Kata-Taldyk, Kara-Suisky district, **Osh**	40.5294	72.7900	5
18/04/2004	E Asia	China	**Maoyang** Township, Wuzhishan City, Hainan	18.9322	109.5367	1
21/04/2004	SE Asia	Indonesia	Kidang Pananjung, near **Bandung** city, West Java	-6.9128	107.6206	15
23/04/2004	SE Asia	Indonesia	Bukit Barisan Mountains, 200km N Padong, Nr Pasaman, Sumatra	2.0333	99.2500	42
23/04/2004	E Asia	China	Majuangou village, **Hengshan** county, Shaanxi	37.9583	109.2817	4
24/04/2004	SE Asia	Indonesia	**Panti** village, Pasaman subdistrict, West Sumatra	0.3667	100.0500	2
25/04/2004	N America	USA	**Aladdin**, N Highway 24, Wyoming	44.6400	-104.1831	1
26/04/2004	C Asia	Kyrgyzstan	Budalyk village, Alay district - **sp. Burdalyk?**	40.3500	73.5000	33
27/04/2004	Middle East	Bahrain	**Malikiya** village (aka Al Malikiyah)	26.0981	50.4867	1
30/04/2004	S Asia	Pakistan	Udhampur, Kashmir	75.2500	32.9167	2
01/05/2004	E Asia	Taiwan	Nr Hsingchen, E Taiwan	24.1667	121.6667	2
01/05/2004	Africa	Kenya	Githimbai village in **Kihuri** area of Othaya, Nyeri district	-0.5500	36.8667	5
07/05/2004	E Asia	China	Gaoyuan Village, **Baihepu** Town, Hunan province	26.7647	112.1708	3
10/05/2004	C Asia	Kyrgyzstan	Kara-Batkak village, Karakolja district (700km S **Bishkek**)	42.8731	74.6003	2
11/05/2004	SE Asia	Indonesia	Sanginora subdistrict, Central Sulawesi			1
13/05/2004	E Asia	China	Ganchuan Town, **Xiushan** County, Chongqing	28.4500	108.9833	11
13/05/2004	Africa	Angola	Gbor-Payee, Nimba county			2
14/05/2004	S Asia	Nepal	Kussum Kanguru, Khumbu region			1
20/05/2004	SE Asia	Vietnam	Trung Ho hamlet, **Ban Ho** village, Sa Pa district	22.2500	103.9500	3
20/05/2004	SE Asia	Thailand	Mae Ramad district, Tak province			4
22/05/2004	C Asia	Tajikistan	**Dushanbe**, Manchi district, Soghd province	38.5600	68.7739	4
24/05/2004	Caribbean	Haiti	Fonds-Verettes	18.3914	-71.8569	1500
24/05/2004	Caribbean	Haiti	Thiotte	18.2500	-71.8500	
24/05/2004	Caribbean	Haiti	Grand Gosier	18.1833	-71.9167	
24/05/2004	Caribbean	Haiti	Belle Anse	19.4500	-72.2167	
24/05/2004	Caribbean	Dominican Republic				21
28/05/2004	M East	Iran	El Borra Mountains			28
28/05/2004	N America	Canada	Lac Paradis, Cote-Nord			2
31/05/2004	E Asia	China	Shuicheng County, Guizhou province			8
01/06/2004	E Asia	China	**Fuling District**, Chongqing Province	29.7167	107.4000	3
01/06/2004	S America	Brazil	**Maceio**, Estado de Alagoas	-9.6667	-35.7167	18
04/06/2004	S Asia	Bangladesh	Banskali, Ctg	22.0417	91.9544	1

Date	Continent	Country	Location	Latitude	Longitude	Fatalities
05/06/2004	E Asia	China	**Xinhua Village**, Wandong Town, Wansheng District, Chongqing	27.8519	111.8989	21
09/06/2004	SE Asia	Indonesia	**Wonorejo hamlet**, Blitar district, East Java	-8.0219	112.6333	2
09/06/2004	S Asia	India	Sunderdhunga Glacier, Uttaranchal			5
14/06/2004	S Asia	India	Baldora, 14 km from **Joshimath**, on the Badrinath and Hemkund Sa	30.5667	79.5667	7
14/06/2004	C Asia	Kyrgyzstan	Gemerjurat district, 70 km from **Batken**	40.0500	70.8333	3
16/06/2004	S Asia	India	Between Veer and Karanjadi stations, 200 km from **Mumbai**	18.9750	72.8258	14
20/06/2004	E Asia	South Korea	**Jungang**, North Chungchong	37.5833	126.9667	1
20/06/2004	S Asia	Bangladesh	**Alinagar**, Nasirabad, Chittagong	23.9000	89.9667	2
23/06/2004	SE Asia	Vietnam	**Mong Sen** village, Trung Chai commune, Sa Pa district in northern L	22.4000	103.8667	3
26/06/2004	E Asia	China	Dalao Mount, **Lingyun County**, south China's Guangxi Zhuang	24.4000	106.5167	7
26/06/2004	C America	Nicaragua	Musun Mountain, Central Nicaragua, near **Rio Blanco**	12.9333	-85.2167	14
27/06/2004	N America	USA	**Mount McKinley**, Alaska.	63.0833	151.0000	1
30/06/2004	E Asia	China	**Yibin City**, Xingwen County, Sichuan	28.7667	104.5667	13
30/06/2004	SE Asia	Philippines	**La Trinidad**, Benguet	16.4550	120.5875	2
30/06/2004	SE Asia	Philippines	**Tabuk**, Kalinga, Cordillera	17.4189	121.4458	3
30/06/2004	SE Asia	Philippines	**Tuba**, Benguet, Cordillera	16.3897	120.5608	1
01/07/2004	SE Asia	Indonesia	**Kragilan** village in Magelang regency, Central Java	-7.4200	110.5528	2
02/07/2004	E Asia	Taiwan	**Alishan**	23.5167	120.8144	2
02/07/2004	E Asia	Taiwan	**Nantou**	23.9089	120.6847	5
03/07/2004	E Asia	Taiwan	**Taichung**	24.2497	120.7158	3
03/07/2004	E Asia	Taiwan	Nantou County			18
03/07/2004	E Asia	China	**Liangjiang** township of Wuming county in the suburbs of Nanning, c	23.4333	108.3667	4
05/07/2004 an	E Asia	China	Dehong prefecture			35
06/07/2003	S Asia	India	Bankpur between Sevoke and Kalijhora, Sikkim, West Bengal			6
06/07/2004	S Asia	India	**Badrinath** to Rishikesh Road, Uttaranchal	30.7333	79.4833	18
06/07/2004	E Asia	China	Yunnan Province			14
09/07/2004	S Asia	Bhutan	Melphey Village, **Trashigang - sp. Tashigang?**	27.3167	91.5667	1
09/07/2004	S Asia	Bhutan	Trashiyangphu, **Wamrong** dungkhag	27.0667	91.5667	1
10/07/2004	S Asia	Bangladesh	**Chittagong**	22.3636	91.8033	3
11/07/2004	S Asia	Nepal	Salle Village, **Ramechap - Ramechhap?**	27.3333	86.0833	2
11/07/2004	S Asia	Nepal	Bhuji, **Ramechap - Ramechhap?**	27.3333	86.0833	2
11/07/2004	S Asia	Nepal	Hatosima Village, **Khotang**	27.0167	86.8500	1
12/07/2004	Europe	Slovenia	? West			1
13/07/2004	S Asia	Nepal	Basamadi, **Makwanpur**	27.4167	85.1333	2
13/07/2004	S Asia	Nepal	**Bhainse**, Makwanpur	27.5000	85.0500	2

Date	Continent	Country	Location	Latitude	Longitude	Fatalities
13/07/2004	S Asia	Nepal	Bahuni Danada, **Khotang**	27.0167	86.8500	2
13/07/2004	S Asia	Nepal	**Khotang**	27.0167	86.8500	1
13/07/2004	S Asia	Nepal	**Sundarpur** village, Sarlahi	27.0167	85.1167	3
13/07/2004	S Asia	Nepal	?			2
13/07/2004	E Asia	Japan	**Tochio**, Niigata	37.4667	139.0000	1
13/07/2004	E Asia	Japan	**Izumozaki**, Niigata	53.5333	138.6833	1
13/07/2004	S Asia	Bhutan	Udzorong, **Trashigang**	27.3167	91.5667	2
14/07/2004	S Asia	Nepal	**Okhaldunga** district	27.3167	86.5000	15
15/07/2004	S Asia	India	Durgasarobar, Guwahati, Assam	26.1500	91.4500	5
15/07/2004	S Asia	India	Fatasil Ambari, **Guwahati**, Assam	26.1000	91.4500	3
15/07/2004	S Asia	India	Pub Sarania, **Guwahati**, Assam	26.1000	91.4500	1
15/07/2004	S Asia	India	Santipur, **Guwahati**, Assam	26.1000	91.4500	1
15/07/2004	S Asia	India	Assam			5
15/07/2004	S Asia	Bhutan	**Tashigang**, Uzorong	27.3167	91.5667	1
16/07/2004	C Asia	Georgia	Svaneti village, Tsrili, **Mestia**, Svaneti	43.0456	42.7297	1
17/07/2004	E Asia	Japan	Shiratogawa river about 7 kilometers up from Lake Tagokurako, **Tad**	37.3500	139.3167	1
18/07/2004	Australasia	New Zealand	Waiohou Valley, SE **Whakatane**	-37.9833	177.0000	1
19/07/2004	E Asia	Japan	**Fukui**	36.3167	139.4500	1
19/07/2004	E Asia	China	**Binyang** County, Guangxi Zhuang	23.2000	108.8000	8
19/07/2004	E Asia	China	**Xiangzhou** County, Guangxi Zhuang	23.6197	107.0575	1
19/07/2004	E Asia	China	**Lingshan** County, Guangxi Zhuang	22.6000	110.5833	4
19/07/2004	E Asia	China	**Huaihua**, Hunan	27.5494	109.9592	2
19/07/2004	S America	Brazil	**Sao Bernardo do Campo**, Sao Paulo	-23.7000	-46.5500	3
20/07/2004	S Asia	Bangladesh	Lama, **Bandarban**	22.2000	92.2167	1
21/07/2004	E Asia	China	Lushan, Zhidong and Nongpo Villages, **Yingjiang** county, Yunnan pr	24.7167	97.9333	12
21/07/2004	E Asia	China	**Huize** county, Yunnan	26.3500	103.4167	3
22/07/2004	E Asia	China	Longyang district, **Baoshan city**	25.1167	99.1500	1
27/07/2004	S Asia	India	Yamunotri, **Uttarkashi** district, Uttaranchal	30.7333	78.4500	6
29/07/2004	S Asia	India	Mizoram			7
30/07/2004	SE Asia	Philippines	**Mati**, Davao Oriental	6.9528	126.2158	2
30/07/2004	S Asia	Pakistan	Millat Road, **Rasoolnagar - sp. Rasulnagar**			3
01/08/2004	S Asia	India	Lokmanya Nagar, **Thane**	19.2000	72.9667	1
01/08/2004	E Asia	Japan	**Kisawa**, Tokushima prefecture	33.8333	134.2500	2
03/08/2004	S Asia	India	Adakkathodu, Kottiyur, **Kannur**	11.8500	73.3667	4
03/08/2004	S Asia	India	**Tehri** Dam, Uttranchal	30.3833	78.4833	29

Date	Continent	Country	Location	Latitude	Longitude	Fatalities
04/08/2004	S Asia	India	Nellikunnu, **Kozhikode**, Kerala	11.2500	75.7667	10
04/08/2004	S Asia	India	Pothumattam, Kullamavu, **Idukki** district, Kerala	9.8500	76.9667	5
05/08/2004	S Asia	India	Vannachichira village, Kerala			10
05/08/2004	SE Asia	Philippines	Purok 4, Barangay San Jose, Nr **Cebu City**	10.3111	123.8917	1
06/08/2004	S Asia	India	Matrunh village of Sansal gram panchayat of **Baijnath** subdivision, D	32.0500	76.6500	4
06/08/2004	S Asia	India	Banganga in **Katra**, 60 km from Jammu, Kashmir	32.9833	74.9500	11
10/08/2004	E Asia	China	Longyan, Fujian			1
10/08/2004	SE Asia	Philippines	Puajas, **Mindanao**	9.6267	123.3814	5
12/08/2004	S Asia	India	Kureshi Nagar, **Kurla**, NE Mumbai	18.7500	77.1333	3
12/08/2004	E Asia	Taiwan	Hualien County			1
13/08/2004	S Asia	India	Kullu district, Himachal Pradesh			2
14/08/2004	S Asia	Pakistan	Amin Drakk (Mountain)			1
15/08/2004	E Asia	China	**Yueqing city**, Zhejiang province	28.1272	120.9536	46
15/08/2004	N America	Canada	Mount Athabasca, Alberta			1
17/08/2004	SE Asia	Philippines	**San Mateo**, Rizal	14.6969	121.1219	5
18/08/2004	E Asia	Japan	Ehime, Shikoku			1
18/08/2004	E Asia	Japan	Toyo Sugawara, Kagawa Prefectural			2
18/08/2004	E Asia	Japan	**Niihama**, Ehime Prefecture	33.9667	133.2667	1
19/08/2004	E Asia	Japan	Shikoku Island			2
19/08/2004	S Asia	Nepal	**Tatopani**, Sindhupalchowk district	27.9500	85.9333	5
20/08/2004	N America	USA	**Inman**, Virgina	36.9103	-82.8028	1
25/08/2004	E Asia	Taiwan	**Wufeng**, Hsinchu	23.9667	120.5000	5
25/08/2004	SE Asia	Philippines	Barangay Silangan, **San Mateo**, Rizal	14.6969	121.1219	1
25/08/2004	S Asia	Pakistan	**Basira**, Muzaffargarh	30.0833	71.0500	5
25/08/2004	E Asia	Taiwan	**Tao-chang**, Hsinchu County	23.8833	120.7333	19
25/08/2004	E Asia	China	Dechang County, Sichuan Province			10
25/08/2004	E Asia	Taiwan	**Hoping**, Taichung	24.0000	120.5667	1
27/08/2004	SE Asia	Philippines	**Baguio City**	16.4164	120.5931	2
28/08/2004	S Asia	Pakistan	**Badan** village, Mamoond Tehsil. near Bajaur agency	34.2708	72.9250	3
02/09/2004	E Asia	China	**Shenmu**, Yulin city, Shaanxi	38.8244	110.4831	7
02/09/2004	S Asia	India	Manchi, Sikkim			5
02/09 to 06/09	E Asia	China	Dazhou, Sichuan			46
02/09 to 06/09	E Asia	China	Rest of Sichuan			75
02/09 to 06/09	E Asia	China	Chongqing			75
04/09/2004	E Asia	China	Dayin Township, **Yilong** County, Nanchong City, Sichuan Province	31.5667	106.4000	9

Date	Continent	Country	Location	Latitude	Longitude	Fatalities
07/09/2004	E Asia	China	Shunzhou Township, **Yongsheng** county, Yunnan Province	26.7000	100.7500	8
07/09/2004	E Asia	Japan	**Togo**, Kagoshima Province	31.8667	130.3333	1
09/09/2004	SE Asia	Vietnam	**Sa Pa** District, Lao Cao province	22.3500	103.8667	2
11/09/2004	Caribbean	Jamaica	**Mount Salus**, near Stony Hill - **sp. Mount Solus?**	18.1000	-77.8833	4
12/09/2004	E Asia	Taiwan	Hsinchu			4
12/09/2004	S Asia	Bangladesh	**Sitakundu**, Chittagong - **sp. Sitakunda**	22.6453	91.6633	5
13/09/2004	SE Asia	Vietnam	**Bat Xat** district, Lao Cai province	22.6000	103.8500	23
14/09/2004	N America	USA	**Kipahulu**, Haleakala National Park, Hawaii	20.6567	-156.0586	1
16/09/2004	N America	USA	Peeks Creek, outside **Franklin**, western North Carolina	35.7211	-80.4992	5
17/09/2004	Caribbean	Dominican Republic	**Santo Domingo**	18.4667	-69.9000	1
17/09/2004	C. America	Panama	**San Miguelito** district	9.0333	-79.5000	3
18/09/2004	SE Asia	Thailand				2
19/09/2004	Caribbean	Haiti	Gonaives	19.4500	-72.6833	3006
22/09/2004	E Asia	China	**Dechang** County, Sichuan Province	27.4064	102.1806	11
22/09/2004	N. America	USA	**Rockport**, Washington	48.4858	-121.5964	1
23/09/2004	S Asia	India	**Nainital**, Uttaranchal	29.3833	79.4500	4
28/09/2004	E Asia	Japan	**Miyagawa**, Mie, western Japan	35.6500	140.5000	7
29/09/2004	E Asia	Japan	**Niihama**, Ehime Prefectuure	33.9667	133.2667	4
07/10/2004	S Asia	India	Jyotikuchi hillock near Kalapahari, Assam **(Guwahati)**	26.5000	91.7500	7
08/10/2004	S Asia	Nepal	Siddhababa, Dobhan VDC, **Palpa**	27.8667	83.4833	15
07/10/2004	S Asia	India	Odalbakra area, Assam			6
08/10/2004	S Asia	India	Dhirenpara, Fatashil Ambari, **Guwahati**, Assam	26.5000	91.7500	6
08/10/2004	S Asia	India	Jorabat on the **Guwahati**-Shillong Road, Assam	26.5000	91.7500	3
08/10/2004	S Asia	India	Jyotinaga, **Guwahati,** Assam	26.5000	91.7500	2
09/10/2004	E Asia	Japan	**Kamakura**, southwest of Tokyo	35.3089	139.5503	1
09/10/2004	S Asia	India	**Mawiong**, Meghalaya	25.5667	91.7167	1
09/10/2004	S Asia	India	Kharkhutta, East Garo Hills, Meghalaya			1
10/10/2004	E Asia	Japan	**Izu**, located in Shizuoka prefecture	26.2369	127.7711	1
15/10/2004	S Asia	India	Dargu in **Shimla** district, Himachal Pradesh	31.1000	77.1667	9
15/10/2004	S Asia	Pakistan	Laiswa Kanar Bila, Neelum Valley, Pakistani Kashmir (45 miles NE	34.3667	73.4667	9
18/10/2004	SE Asia	Thailand	Kram village, Krabi Province			3
20/10/2004	E Asia	Japan	Ehime, Shikoku			1
20/10/2004	E Asia	Japan	Ehime, Shikoku			2
20/10/2004	E Asia	Japan	Ehime, Shikoku			1
21/10/2004	E Asia	Japan	**Tamano**, Okayama prefecture	34.4833	133.9500	5

Date	Continent	Country	Location	Latitude	Longitude	Fatalities
21/10/2004	E Asia	Japan	Kyoto prefecture			2
21/10/2004	E Asia	Japan	Hyogo prefecture			1
21/10/2004	E Asia	Japan	Awaji			1
22/10/2004	E Asia	Japan	Myokenmachi, Chuetsu region, **Niigata** Prefecture	37.4500	138.8500	2
22/10/2004	SE Asia	Malaysia	**Batu Pahat**	1.8500	102.9333	1
23/10/2004	E Asia	Japan	Nagaoka City, Niigata	37.4500	138.8500	2
27/10/2004	S. America	Colombia	Near **Riosucio**, Caldas	5.4244	-75.7058	7
30/10/2004	S. Asia	India	Pandikkuppam, near **Chinna Salem**, Villupuram district	11.6500	78.9000	2
03/11/2004	SE Asia	Indonesia	Talang Lindung, Kerinci			2
05/11/2004	SE Asia	Malaysia	Taman Harmonis, Gombak			1
12/11/2004	Caribbean	Trinidad and Tobago	**Delaford**, Tobago	11.2667	-60.5667	2
14/11/2004	Europe	Italy	**Lecco** (N Italy)	45.8500	9.3833	2
14/11/2004	Caribbean	Puerto Rico	**Adjuntas**	18.1647	-66.7225	1
15/11/2004	Europe	Norway	Kongsnes, between Hyyanger and Balestrand			1
17/11/2004	SE Asia	Indonesia	**Alor-Kecil**, East Nusa Tenggara	-8.2667	124.4000	1
17/11/2004	C. Asia	Tajikistan	Nurobod district, Central Tajikistan			6
20/11/2004	N. America	USA	**Highland**, California	34.1283	-117.2078	1
20/11/2004	S. America	Colombia	**Medellin**, 400 km northwest of Bogota, Antioquia province	6.2914	-75.5361	2
20/11/2004	S. America	Colombia	**Sabaneta**, Antioquia province	6.1500	-75.6000	2
20/11/2004	SE Asia	Vietnam	**Lao Cai**	22.4833	103.9500	2
22/11/2004	SE Asia	Indonesia	**Lingkas** in Tarakan city, East Kalimantan.	3.2833	117.6167	2
23/11/2004	SE Asia	Philippines	**Dingalan** town, Aurora, East Luzon	15.3881	121.3928	29
24/11/2004	S. Asia	India	Asarva, Gujarat			6
27/11/2004	SE Asia	Vietnam	Tay Tra district			5
28/11/2004	SE Asia	Philippines	**Vinzons** town on the Bicol peninsula, Luzon	14.1781	122.9072	1
29/11/2004	SE Asia	Philippines	Barangay (village) Paltic, **Dingalan** town, Aurora	15.3881	121.3928	1
29/11/2004	SE Asia	Indonesia	**Sumbul**, North Sumatra,	2.7667	98.2500	1
29/11/2004	SE Asia	Philippines	**Real**, Quezon	14.6625	121.6047	250
29/11/2004	SE Asia	Philippines	**Infanta**, Quezon	14.7425	121.6494	412
29/11/2004	SE Asia	Philippines	**General Nakar**, Quezon	14.7631	121.6350	262
30/11/2004	SE Asia	Philippines	Barangay Bagong Buhay 2 in **San Jose del Monte** City, Bulacan pro	14.8139	121.0453	1
30/11/2004	SE Asia	Philippines	**Dumingan** town, Aurora province	8.1667	123.3333	100
30/11/2004	SE Asia	Philippines	Barangay Villa, Ma. **Aurora** town, Luzon	17.0000	121.3333	3
02/12/2004	SE Asia	Malaysia	Taman Utama, Bercham, **Ipoh**	4.5833	101.0833	2
03/12/2004	SE Asia	Philippines	Viewpoint, **Banaue**, Ifugao, Baguio?	16.9186	121.0592	2

Date	Continent	Country	Location	Latitude	Longitude	Fatalities
03/12/2004	E Asia	China	Nayong County, Guizhou Province			44
03/12/2004	E Asia	Taiwan	**Feng-pin** Creek, Hualien	23.6000	121.5167	1
05/12/2004	SE Asia	Indonesia	**Sipahutar** district, North Tapanuli regency, North Sumatra	2.1167	99.1000	2
11/12/2004	SE Asia	Thailand	**Yala**, 760 kilometres south of Bangkok	6.5428	101.2836	1
12/12/2004	SE Asia	Philippines	Barangay Bulao, Balete, **Tinambac**, Camarines Sur	13.8175	123.3253	8
14/12/2004	SE Asia	Indonesia	**Cimenga** subdistrict, Kuningan regency	7.0833	108.3333	1
14/12/2004	S Asia	Sri Lanka	**Welimada**, Central Province	6.9011	80.9228	5
15/12/2004	N America	USA	**Melissa**, Texas	33.2858	-96.5725	1
17/12/2004	S Asia	Pakistan	A "suburb village" in **Orakzai**.	31.0556	66.7708	2
26/12/2004	SE Asia	Philippines	San Antonio and Datu Intan, Sta. Maria, Davao del Sur			12
27/12/2004	SE Asia	Indonesia	**Guyangan** village, Loanu	7.8333	109.9500	3
		216 landslides	27 multiple landslide events			7028

APPENDIX 2

The number of recorded landslide fatalities per country

Region	Sub-region	Country	No. of l/s events	No. of multiple l/s events	No. of fatalities
Africa	North	Morocco	1		230
	Sub-Saharan	Angola	3		23
		Kenya	4		26
		Cameroon	1		21
		Ethiopia	4		43
		Uganda	5		57
		Mozambique	2		93
		Nigeria	5		52
		Congo	2	1	63
		Tanzania	1		13
	South Africa	South Africa	1		34
Total		**11**	**29**	**1**	**655**
Americas	North	USA	18		48
		Canada	2		3
	Caribbean	Barbados	1		4
		Bermuda	2		2
		Dominican Republic	2	1	23
		Haiti	4	2	4519
		Jamaica	1		4
		Puerto Rico	1		1
		Trinidad and Tobago	1		2
	Central	Costa Rica	1		9
		El Salvador	3		558
		Guatemala	3		126
		Mexico	6	1	382
		Nicaragua	1	1	1694
		Panama	1		3
	South	Bolivia	2	2	221
		Brazil	11	4	517
		Colombia	17	4	1479
		Ecuador	11		196
		Guyana	1		10
		Peru	14		527
		Venezuela		1	30000
Total		**22**	**103**	**16**	**40328**

Appendix 2 continued

Region	Sub-region	Country	No. of l/s events	No. of multiple l/s events	No. of fatalities
Asia	South	Afghanistan	4		537
		Bangladesh	11	2	151
		Bhutan	4		5
		India	76	11	1726
		Nepal	61	7	1201
		Pakistan	20		136
		Sri Lanka	6	1	315
		Tibet	1		16
	Central	Georgia	1		1
		Kazakhstan	1		29
		Kyrgyzstan	7	1	258
		Russia	3		160
		Tajikistan	10		183
	East	China	86	17	2250
		Japan	33	2	208
		Korea, Rep (North)	1		19
		Korea, Dom Rep (South)	6		31
		Taiwan	14	2	487
	South East	Brunei	1		1
		Malaysia	13		100
		Indonesia	50	5	1260
		Philippines	45	6	1823
		Thailand	5	1	132
		Vietnam	15		164
Total		**24**	**474**	**55**	**11193**
Australasia	Australia and New Zealand	Australia	3		29
		Micronesia	1	1	59
		New Zealand	1		1
		Papua New Guinea	4		88
	Pacific Islands	American Samoa	1		6
		Fiji	1		6
		French Polynesia		2	23
		Vanuatu	1		1
Total		**8**	**12**	**3**	**213**

Appendix 2 continued

Region	Sub-region	Country	No. of l/s events	No. of multiple l/s events	No. of fatalities
Europe		Bosnia-Hercegovenia	1		6
		Bulgaria	1		2
		Greece	1		1
		Italy	8		177
		Norway	2		5
		Portugal	1	1	34
		Romania	1		15
		Slovenia	1		1
		Spain	1		84
		Switzerland	1		16
		Turkey	2	1	60
		UK	1		1
Total		**12**	**21**	**2**	**402**

Middle East		Bahrain	1		1
		Iran	1	1	109
		Saudi Arabia		1	30
		Syria	1		80
Total		**4**	**3**	**2**	**220**