LANDSLIDE RISK QUANTIFICATION ALONG TRANSPORTATION CORRIDORS BASED ON HISTORICAL INFORMATION

Pankaj Jaiswal
Examing committee

Prof. dr. ir. A. Veldkamp University of Twente
Prof. dr. ir. M.F.A.M. van Maarseveen University of Twente
Prof. dr. D. Petley Durham University, UK
Dr. F. Nadim NGI, Norway
Dr. P.K. Champati Ray IIRS, India

ITC dissertation number 191
ITC, P.O. Box 6, 7500 AA Enschede, The Netherlands

ISBN 978-90-6164-311-1
Cover designed by Benno Masselink / Job Duim
Printed by ITC Printing Department
Copyright © 2011 by Pankaj Jaiswal

This doctoral dissertation was produced with the support of:

- Faculty of Geo-information Science and Earth Observation, University of Twente, The Netherlands
- Geological Survey of India, 27 J. Nehru road, Kolkata, India
LANDSLIDE RISK QUANTIFICATION ALONG TRANSPORTATION CORRIDORS BASED ON HISTORICAL INFORMATION

DISSERTATION

to obtain
the degree of doctor at the University of Twente,
on the authority of the Rector Magnificus,
prof.dr. H. Brinksma,
on account of the decision of the graduation committee,
to be publicly defended
on 4 July 2011 at 15.30 hrs

by
Pankaj Jaiswal

born on 15 June 1976
in Hazaribag, India
This thesis is approved by
Prof. dr. Victor G. Jetten, promoter
Dr. Cees J. van Westen, assistant promoter
Dr. K. Ayyasami, assistant promoter
to my family
Abstract

Landslides are viewed as a persistent problem along transportation corridors in mountainous regions. Landslides not only cause damage to properties (alignments, buildings, vehicles, etc.) and life, but also affect the society by disrupting the utility services and economic activities. In order to reduce the impact of landslides on society it is necessary to quantitatively estimate the risk from potential landslides, and carry out a cost-benefit analysis of various risk reduction measures.

For the analysis of landslide risk we require information on historical landslides and data on past losses. The availability of a substantially complete landslide inventory is by far the most important. However, inventories prepared from either remote sensing data or from historical records are seldom complete. Only for specific cases landslide inventories could be complete such as those recording cut slope failures along transportation corridors, collected for maintenance purposes. This research utilises such maintenance records to prepare a substantially complete landslide inventory along transportation lines. An approach is presented to use this inventory for quantifying landslide hazard and risk along transportation lines and use this for the natural slopes where landslide data are scarce. The historical records were used in rainfall threshold analysis, which later formed the basis for the identification of hazard from slope failures on natural slopes and for the development of a landslide warning system.

The research was conducted along a transportation corridor with a road and a railway alignment in the Nilgiri hills in southern India. Historical records belonging to the railway and geotechnical units were used to obtain a multi-temporal landslide inventory for a 23-year period from 1987 to 2009. A substantially complete inventory was obtained for landslides initiating from cut slopes along the transportation lines. In contrast, only little information was available for landslides affecting natural slopes above the transportation lines. Most landslides were shallow translational debris slides and debris flows triggered by rainfall. On natural slopes most landslides occurred as first-time failures.

Various analyses were performed to quantify landslide risk along the road and the railroad and the surrounding areas. A Gumbel analysis was carried out to determine the frequency of landslides on cut slopes and on natural slopes for certain units of the transportation line. Logistic regression analysis was carried out to model the susceptible areas to landslides on natural
slopes. Rainfall threshold analysis was used to estimate the temporal probability of landslides, and magnitude-frequency analysis to obtain the probability of landslide size. These data were combined in an analysis of landslide initiation hazard on cut and natural slopes. Landslide run-out analysis was carried for landslides on natural slopes. Landslide vulnerability was established for landslides with different magnitudes and for different elements at risk. Landslide hazard and risk estimation was done using landslide events that occurred between 1987 and 2007 and the results were validated using landslides that occurred in 2008 and 2009. As a final output direct risk was quantified for properties (alignments, vehicles, buildings, and plantations) and people (commuters and residents) and indirect risks due to the traffic interruption. The research also presented the perception of Nilgiri people to landslide risk and the use of the obtained hazard and risk information in reducing landslide risk to the society.

The results provided a quantitative estimate of total annual landslide losses, expressed in monetary value (US$) for properties and in annual probability of death for people. An F-N curve was used to express the societal risks. The results are of important societal value and will provide inputs for planning risk reduction strategies, for developing risk acceptance criteria and for financial analysis for possible damage in the study area. The methodology provides a cost-effective approach to estimate direct and indirect landslide risks. The methods can be applied elsewhere if a similar historical landslide data is made available.
Acknowledgements

It is indeed a moment of great pleasure and immense satisfaction for me to express my profound gratitude towards my supervisors Dr. Cees J. van Westen and Dr. K. Ayyasami and promoter Dr. V. G. Jetten for their zeal and enthusiasm which were of great inspiration to me. I thank them for their able guidance and untiring attention which they bestowed on me right from the inception to the successful completion of this research work. I am thankful to Dr. V. G. Jetten and Dr. Cees J. van Westen for accepting me as a PhD student at the Faculty of Geo-information Science and Earth Observation (ITC).

The inception of this research would not have been possible without the constant effort of Dr. N. Rajendran, Director (Retd.), Geological Survey of India (GSI) who personally drafted the MoU signed between GSI, NRSC and ITC, The Netherlands. I am thankful to Dr. K.S. Misra, Dy.D.G. (Retd.); Shri. V. Balachandran, Dy.D.G. (Retd.), Dr. P. N. Razdan, Dy.D.G. (Retd.) and GSI for allowing me to take up this research work.

Thanks are due to various institutions that have directly or indirectly supported me in this work. I am highly indebted to Shri Gopikrishnan, Asst. Director, GTC and M. Franklin, founder of the Rescue operation unit for providing basic landslide data and photographs. I sincerely acknowledge the help of officials of the Southern railway, Coonoor for providing me accommodation, and landslide and rainfall data of immense value. I am thankful to the managers of Singara, Glandale, Adderley, Muteri, Carolina and Benhope tea estates and officials of the horticulture department for the rainfall and landslide damage data relevant to my research area.

This research would not have been possible without the support of GSI. I am grateful to Dr. K.R.K. Prasad, Shri. M. Raju and Shri M. Chakradhar for their constant support and guidance. I thank GSI for providing the logistics needed for the field work.

Numerous colleagues have helped me during the course of my research. I am grateful to Saibal, Tapas, Ishwar Das, Sehkar, Ajay, Xuanmei, Enrique, Byron, Rishiraj, Debanjan for their time to time suggestions which helped me improving my work. Besides, the critical comments from several anonymous reviewers were extremely helpful in improving the articles.

I gratefully acknowledge the support extended by Loes, Christie, and Marjolein during my stay in ITC. I would like to express my thankfulness to
all staff members of the ESA department, Student affairs and all technical departments for their kind support. In fact, many people were involved directly or indirectly in the success of this research. Since at this moment it is difficult to memorize all of them, I would like to apologize for any person I forgot to mention.

Back home, I would like to express my sincere thanks to my mother Mrs. Vidya Jaiswal, my father Mr. Krishna Kishore Jaiswal, my brothers Dr. Rakesh and Niraj Jaiswal, my sister in law Mrs. Sushmita Jaiswal and last but not the least my wife Mrs. Utpala Jaiswal for their inspiration, moral support and love which enabled me to complete this work.

During my PhD I have received the best gift of my life, Piyu, my daughter. I am bit unfortunate of not staying close to her during her birth and later but I hope this sacrifice will be worth somehow in the future.

Pankaj Jaiswal
Table of Contents

Abstract .................................................................................................................. i  
Acknowledgements ............................................................................................... iii 
Table of Contents .................................................................................................. v  
List of figures .......................................................................................................... viii 
List of tables ........................................................................................................... xi  
Chapter 1: Introduction ........................................................................................ 1  
  1.1 Research problem ......................................................................................... 3  
  1.2 Motivation for research ............................................................................... 6  
  1.3 Research questions ....................................................................................... 7  
  1.4 Research objectives ..................................................................................... 8  
  1.5 Thesis outline ............................................................................................... 9  
Chapter 2: Study area ......................................................................................... 13  
  2.1 Geomorphology and Geology ................................................................. 13  
  2.2 Land use ..................................................................................................... 15  
  2.3 Rainfall characteristics .............................................................................. 16  
  2.4 Past landslides and loss ............................................................................. 17  
  2.5 Previous work on landslide susceptibility .............................................. 18  
Chapter 3: Landslide inventory ......................................................................... 21  
  3.1 Introduction ................................................................................................ 21  
  3.2 Historical data sources and types of information .................................... 23  
  3.3 Method used for inventory mapping ....................................................... 25  
  3.4 Source of errors, limitations and uncertainty in inventory mapping .......... 28  
  3.5 Summary statistics of the landslide inventory .......................................... 30  
  3.5.1 Landslide characteristics along the railroad ....................................... 31  
  3.5.2 Landslide characteristics along the road .......................................... 35  
  3.5.3 Landslide characteristics on natural slopes ...................................... 35  
  3.6 Evaluation of triggering events ................................................................. 37  
  3.7 Discussion and conclusions ..................................................................... 40  
Chapter 4: Analysis of temporal and size probability ....................................... 43  
  4.1 Assessing the temporal probability of landslide events ........................ 43  
  4.1.1 Rainfall distribution ............................................................................. 44  
  4.1.2 Methodology for temporal probability assessment ............................ 46  
  4.1.3 Determination of the rainfall thresholds ........................................... 47  
  4.1.4 Determining temporal probability ..................................................... 52  
  4.2 Classification of landslide size .................................................................. 57  
  4.2.1 Landslide size definitions .................................................................... 57  
  4.3 Assessing the probability of landslide size .............................................. 59  
  4.3.1 Analyzing the volume-frequency relationship .................................... 61  
  4.3.2 Probability density of landslide volumes in different years .............. 63  
  4.3.3 Effect of terrain and rainfall on the v/f distribution ............................ 65  
  4.3.4 Probability of landslide volume .......................................................... 68  
  4.4 Discussion and conclusions .................................................................... 70  
  4.4.1 Temporal probability of landslide events ........................................ 70  
  4.4.2 Landslide size probability ................................................................. 73  
Chapter 5: Landslide hazard analysis ............................................................... 77  
  5.1 Introduction ............................................................................................... 77
Annexes in supplementary CD-ROM
List of figures

Figure 1.1 Natural disasters in India during the period 1901 to 2010 ........ 2
Figure 1.2 Structure of the thesis .......................................................... 10
Figure 2.1 Location of the transportation corridor .................................. 14
Figure 2.2 Distribution of different types of land use ............................... 16
Figure 2.3 Rainfall variations in the period from 2002 to 2006 .......... 18
Figure 2.4 Part of the landslide susceptibility map of the Nilgiri hills ... 20
Figure 3.1 Marapallam landslide as viewed in different years ............... 22
Figure 3.2 Type of data present in the railway slip register .................. 26
Figure 3.3 Type of data recorded in graph sheet ................................... 27
Figure 3.4 Criteria adopted for the identification of old landslides ......... 28
Figure 3.5 Type of landslide information obtained after field check ....... 28
Figure 3.6 Annual distributions of the recorded landslides .................... 30
Figure 3.7 Monthly distributions of the recorded landslides ................... 31
Figure 3.8 Landslide inventory map .................................................... 32
Figure 3.9 Type of landslides along the railroad .................................. 33
Figure 3.10 Spatial distribution of landslides from 1992 to 2007 along the railroad ............................................................... 34
Figure 3.11 Type of landslides on cut slopes along the road ................. 36
Figure 3.12 Type of landslides on natural slopes ................................. 36
Figure 3.13 Temporal evolution of landslides near Katteri .................... 37
Figure 4.1 Location of sections and rain gauges for determining rainfall thresholds ................................................................. 45
Figure 4.2 Rainfall during landslide events at six rain gauge stations .... 46
Figure 4.3 Envelope curves for landslides ........................................... 50
Figure 4.4 Validation of the threshold for the section east of Buriyar .... 52
Figure 4.5 Spatial validation of the threshold along the railroad .......... 53
Figure 4.6 Annual temporal probability of landsliding on cut slopes ....... 55
Figure 4.7 Frequency distribution of landslides along the road in different temporal probability classes ............................... 56
Figure 4.8 Histogram and probability density of landslide volume for the period 1987 to 2007 .................................................. 62
Figure 4.9 Histogram and probability density of landslide volumes of 14 November 2006 event .................................................. 62
Figure 4.10 Probability density of landslide volumes for different years .... 65
Figure 4.11 Types of curve observed in the probability density distribution of landslide volumes in different years .......... 66
Figure 4.12 Probability of landslide volumes on natural slopes .......... 71
Figure 5.1 Flow diagram for hazard assessment along road and railroad .. 82
Figure 5.2 Gumbel plot for km-14 of the railroad ............................... 85
Figure 5.3  Total number of landslides in different return periods along the railroad .................................................................87
Figure 5.4  Parameters and process adopted for the rainfall threshold-based assessment of landslide hazard .........................90
Figure 5.5  Landslide preparatory factors ..................................................97
Figure 5.6  Location of landslide source and run-out areas on natural slopes .................................................................98
Figure 5.7  Graphs of cumulative relative frequency of distances at known landslide locations and non-landslide locations ......99
Figure 5.8  Receiver operator characteristic curve ..................................103
Figure 5.9  Parameters and process adopted for the inventory-based landslide hazard assessment ............................................106
Figure 5.10  Map showing the estimated probability of landslides obtained using logistic regression analysis ..................109
Figure 5.11  Graph showing success rate curve (model fit) .................111
Figure 5.12  Landslide susceptibility map showing estimated spatial probability values per slope-unit ..............................111
Figure 5.13  Examples of landslide hazard maps ..................................113
Figure 5.14  Scatter plot between the landslide run-out distance and volume ..................................................................116
Figure 6.1  Flow diagram for landslide risk analysis ..............................130
Figure 6.2  Schematic diagram depicting the method used to estimate risk using the run-out distance .........................132
Figure 6.3  Location of the elements at risk ................................................133
Figure 6.4  Landslide damage information used for vulnerability assessment ........................................................................137
Figure 6.5  Building types in the study area .............................................140
Figure 6.6  Nilgiri toy train at Hillgrove railway station and train crossing a half tunnel structure in a landslide zone ..........152
Figure 6.7  Specific risk to landslide initiation displayed as risk curves ....155
Figure 6.8  Specific risk to different building types displayed as risk curves .....................................................................156
Figure 6.9  Percentage distribution of building types in different susceptible zones ............................................................156
Figure 6.10  Estimated monetary losses due to landslide initiations over a 10 year period ......................................................157
Figure 6.11  F-N plots for people occupying the buildings ......................160
Figure 6.12  Risk curve for total landslide losses in the study area ..........163
Figure 7.1  Type of landslides triggered in 2009 and damages caused .....173
Figure 7.2  Damages to houses located on the natural flow path of a stream .....................................................................174
Figure 7.3  Landslides triggered on natural slopes around Katteri area ....175
Figure 7.4  Spatial distributions of landslides of 2009 events ............... 176
Figure 7.5  Validation of the threshold equation for natural slopes ......... 178
Figure 7.6  Probability density of landslide volumes of 2006 and 2009 event ................................................................................. 179
Figure 7.7  Prediction skills of the landslide susceptibility model .......... 181
Figure 8.1  Framework for Landslide Risk Management .................... 187
Figure 8.2  Landslide information for risk reduction planning ............. 194
Figure 8.3  Hazard information for risk reduction planning ............... 196
Figure 8.4  Slope stabilization measures ........................................ 199
Figure 8.5  Criteria to issue warning based on rainfall threshold........... 202
Figure 8.6  Operating procedure of the early warning system based on rainfall thresholds......................................................... 204
Figure 8.7  Participatory mapping exercises ..................................... 210
Figure 8.8  Mock drills .................................................................... 211
List of tables

Table 3.1 Main characteristics of landslide inventory along the railroad, road and on natural slopes .............................................................. 33
Table 3.2 Main landslide triggering events in the period from 1987 to 2007 ..................................................................................... 39
Table 3.3 Characteristics of landslides on cut slopes triggered by 14 November 2006 event along the railroad and the road ...... 40
Table 4.1 Temporal probability of landslides along different units of the railroad ............................................................................. 56
Table 4.2 Size classification of debris slides and debris flowslides ........ 59
Table 4.3 Characteristics of the probability density distribution of rainfall-induced debris slides volume for different years .......... 66
Table 4.4 Terrain characteristics along the railroad ................................ 67
Table 4.5 Probability of landslide size on cut slopes............................ 69
Table 5.1 Number of landslides in different return periods along the road ......................................................................................... 86
Table 5.2 Landslide hazard along the railroad in a 50-year return period ......................................................................................... 88
Table 5.3 Landslide hazard along the road in a 50-year return period ..... 88
Table 5.4 Variation of contrasts in different factor classes with respect to the known landslide occurrences ......................... 100
Table 5.5 Coefficients derived from logistic regression model .............. 104
Table 5.6 Number of landslides expected on natural slopes in different return periods ................................................................. 108
Table 5.7 Temporal probability of landslide events ......................... 108
Table 5.8 Error matrix ........................................................................ 110
Table 5.9 Percentage of study area in different hazard classes .......... 114
Table 5.10 Example of hazard probability calculation ....................... 114
Table 5.11 Estimated vulnerability of elements at risk located in landslide initiation areas ................................................................. 138
Table 5.12 Estimated vulnerability of elements at risk located within landslide run-out paths ......................................................... 138
Table 5.13 Estimated vulnerability for elements at risk affected by a landslide from cut slopes ......................................................... 139
Table 5.14 Vulnerability of people in buildings impacted by a landslide .... 141
Table 5.15 Direct specific risk per kilometer of the railroad ....................... 153
Table 5.16 Direct specific risk per kilometer of the road ...................... 154
Table 5.17 Landslide risk in the study area for different return periods for both landslide initiation and landslide run-out ..... 157
Table 5.18 Direct specific risk for vehicles and train ............................. 158
Table 6.9 Direct specific risk of the person most at risk using vehicle and train ............................................................. 158
Table 6.10 Indirect specific risk due to additional fuel consumption ......... 160
Table 6.11 Indirect specific risk due to additional ticket cost .................. 160
Table 6.12 Indirect specific risk to local business .................................. 161
Table 6.13 Indirect specific risk to the railway ........................................ 161
Table 7.1 Statistics of landslides triggered by the November 2009 events .......................................................................... 176
Table 7.2 Validation of exceedance of rainfall threshold and occurrence of landslide events during 2008 and 2009 ............ 178
Table 7.3 Validation of the landslide hazard along the railroad ............ 182
Table 8.1 Different end users and their requirements ....................... 192
Table 8.2 Cost and benefit of different slope treatment measures ........ 200
Table 8.3 Type of end users and their activities during warning phase .. 205
Chapter 1: Introduction

Landslides are one of the common natural as well as man-made hazards in mountainous terrain. It involves movement of a mass of rock, debris, or earth down a slope, under the influence of gravity (Varnes, 1978; Cruden, 1991; Cruden and Varnes, 1996). Landslides can be triggered by a variety of natural phenomena that causes a rapid increase in shear stress or decrease in shear strength of slope-forming materials, such as earthquakes, rainfall, rapid snow melting, storm waves and volcanic eruptions (Dai et al., 2002; Guzzetti et al., 2005). Among all, rainfall is the most common trigger. Landslides are triggered by both high intensities and short duration rainfall (Glade, 1998) as well as prolonged rainfall (Church and Miles, 1987).

Landslides are generally isolated processes which individually may not be very large in size but can occur with a high frequency in a region and cause substantial damage to life and property (van Westen et al., 2006). Over the years it is expected that landslides will cause more damage to properties than any other geological hazard (Varnes, 1984; Petley et al., 2005). The expected increase in landslide disasters in future is because of overexploitation of natural resources, rapid deforestation, change in climate, and increase in hill population and uncontrolled excavations resulting in a higher susceptibility of surface soil to instability, and higher vulnerability of the exposed population (Nadim et al., 2006; Hoyois et al., 2007). In the latter half of the 20th Century, the increase in hill tourism, hydroelectric projects and increase of hill population because of the human desire for living in natural and serene environments have resulted in a rapid increase of infrastructure developments, such as roads and railroads, new settlements, etc. As a result of these developments more and more hill slopes are excavated 'indiscriminately' without following proper engineering standards and left exposed. Examples are common in many developing countries, including India, where excavated slopes are left unsupported due to various reasons, including the high treatment costs. These untreated slopes often result in slope failures and develop into landslides of larger dimensions with passage of time. Along transportation corridors such excavated slopes may generate landslides that not only affect the alignments, vehicles and people, but also the society by disrupting the economic activities (van Westen et al., 2006). Studies have indicated that the estimated indirect economic loss resulting from the blockage of transportation lines has in fact much larger consequences than the actual direct loss caused by landslides (Schuster and Fleming, 1986; Zezere et al., 2007; Sterlacchini et al., 2007).
Landslides are recognized as the third type of natural disaster in terms of worldwide importance (Ziliman, 1999; Castellanos, 2008). In the period from 1901 to 2010 landslides alone have caused 52,831 deaths around the world and resulted in loss of more than US$6 billion (OFDA/CRED, 2010). In India, they are ranked as seventh in the list of major natural disasters by number of deaths reported (OFDA/CRED, 2010). Figure 1.1 shows the statistics of the major natural disasters, in terms of the number of disasters and people killed, that affected India during the period 1901 to 2010 (OFDA/CRED, 2010). During this period, landslides have been reported to cause about 4,000 deaths in 36 events and resulted loss of about US$4.5 million. In another study, Mathur (1982) estimated the annual loss of nearly US$1 billion for the total 89,000 km of roads in the landslide prone areas of India.

Figure 1.1 Natural disasters in India during the period 1901 to 2010 (OFDA/CRED, 2010).

The statistics of the number of landslides, and associated economic and human losses, in fact, are expected to be much higher than documented by OFDA/CRED (2010) and Mathur (1982). The OFDA/CRED database clearly indicates that only major landslides have been recorded during the last century. The statistical underestimation of landslide impact in global and national databases could be due to several reasons, including: (i) the fact that most damage and human losses actually caused by landslides are attributed to the main triggers such as storms or earthquakes, (ii) many disaster databases apply a minimum threshold of victims or economic losses for disaster impact but since landslides are localized phenomenon and they do not cause such levels of damage as other types of events, and therefore the losses are often not recorded (Castellanos, 2008), (iii) most landslides, particularly along transportation corridors, are individually small in size and
do not always result in direct life loss and therefore they are rarely recorded in national databases, and (iv) indirect economic losses resulting from traffic disruption are mostly not estimated for landslides, which further leads to underestimation of the total landslide loss. The incompleteness of landslide data in the national database not only underestimates the actual impact of landslide disasters but decreases its priority for mitigation and national policies.

In order to perceive a landslide disaster and to reduce its impact on the society it is necessary to realistically assess the expected disaster losses. The assessment involves quantitative estimation of both direct and indirect risks, which in turn requires numerous input parameters to quantify the individual component of hazard, vulnerability and elements at risk (Fell et al., 2008).

In the last decades many advances in landslide related studies have been made. Most of the studies are related to landslide identification, dynamic modelling and susceptibility analysis, but relatively few studies have been carried out on the quantitative analysis of landslide hazard and risk. The limited number of publications on landslide hazard and risk estimation is mostly due to the unavailability of a substantially complete landslide inventory and due to the lack of sufficient information on landslide damages, frequency of events and landslide sizes (van Westen et al., 2006). Since most of the above information can only be obtained from historical records the availability of such records, thus becomes crucial. In most countries there is no single agency that has the responsibility of maintaining historical landslides and damage records, rather different agencies maintain records of their area of interest. This result in incomplete and biased databases both with respect to the area covered and to the time period investigated (Ibsen and Brunsden, 1996). The insufficient historical records on landslides, in fact, makes estimation of landslide risk difficult in most countries. More thrust is therefore needed to obtain inventory of historical landslides and associated damages so that assessment of landslide risk becomes possible.

1.1 Research problem

In recent years, with the growing demand of safe hill roads and low risk areas for settlements, research efforts related to landslide risk analysis and risk reduction are also increasing. Risk analysis is especially relevant in developing countries where spatial planning is mostly given much less attention, leading to developments in hazardous areas, and due to the high costs of relief and recovery after landslide disasters take place. In developing countries societal and economic problems are often so large and serious that little attention is given to potential landslide problems, which are generally
Introduction

localized and affect a small section of the society. In such countries, the limited resources are primarily used to improve health and education or to promote the economy, and a very small fraction is made available for disaster prevention, including risk analysis. Therefore, efforts are needed to improve the more economical approaches of carrying out landslide risk analysis, and demonstrate the cost-effectiveness of risk reduction measures.

After analyzing the landslide research carried out in India and other parts of the world, the following important problems in landslide hazard and risk studies with relevance to developing countries were observed:

- A systematic procedure for landslide risk analysis requires a substantially complete landslide inventory with known dates of landslide occurrence, information on the magnitude of triggers, details of the damage caused by landslides, environmental factors and elements at risk. Out of these, the historical information on landslide occurrences is the most important because it gives insight into the frequency of the phenomena, the types involved, the volumes and the damage that was caused. The most common way of obtaining landslide information is through inventory mapping using aerial photographs or satellite images (Rib and Liang, 1978). This method is effective for large areas, but has certain drawbacks: the remote sensing data are not only very expensive but are seldom available for all landslide dates and for all areas, the old images lack stereoscopy and are difficult to interpret, the small landslides are often overlooked during photo-interpretation (Brardinoni et al., 2003). Also the unavailability of information on the exact date of landslide occurrence makes it difficult to correlate the landslide with the trigger, such as rainfall (van Westen et al., 2006). Furthermore, if remote sensing data are not available after all major landslide triggering events the actual frequency of landslides in the area remains unknown. Given the above limitations, more effort is needed to look for other sources of landslide information. Sources that are reproducible, complete, cost-effective and relevant to landslide hazard and risk mapping.

- The probability of landslide size (area or volume) forms an important parameter in landslide hazard and risk analysis. Landslide size is often used as a proxy for landslide intensity and therefore the understanding of the size-frequency relationship of landslides is important (Hungr et al., 1999, 2008; Guzzetti et al., 2002). Several researchers have studied this relationship using different types of inventories (e.g., Fuji, 1969; Stark and Hovius, 2001; Guthrie and Evans, 2004, etc.) but no standard distribution pattern is defined between landslide size and frequency. Some relate this distribution with negative power-law function for all
range of sizes while few fit power-law functions only for sizes above a certain threshold value. Also very little is known about the probability distribution of landslide volume along transportation corridors, where the volume can range from a cubic meter to several thousand cubic meters (Dai and Lee, 2001; Luino, 2005). Since probability of size is an important parameter in landslide risk analysis therefore a more detail investigation is needed particularly with reference to cut slopes along transportation corridors.

- For a quantitative landslide hazard analysis we require information on the spatial probability, the size probability, and the temporal probability of landslide initiation and run-out. Numerous publications on the assessment of the spatial probability of landslides are available (e.g., Soeters and van Westen, 1996; Chung and Fabbri, 1999; Guzzetti et al., 2005; Lee and Pradhan, 2006, etc.). The estimation of temporal probability is the most difficult because it requires a substantially complete landslide inventory, which is seldom available (van Westen et al., 2006). Sometimes technical offices such as road and railway maintenance units maintain continuous records of cut slope failures along transportation corridors (Fell et al., 1996). Such records can be used to estimate hazard along transportation lines based on the magnitude-frequency relationship of landslides (e.g., Hungr et al., 1999). Incorporation of the temporal probability into susceptibility maps for natural slope failures is difficult, particularly when landslides are small and few in number. In such cases, event-based landslide maps with frequency assessment (e.g., Coe et al., 2000; Glade, 2001; Guzzetti et al., 2005), or physically-based modelling (e.g., Frattini et al., 2004) are used to estimate the frequency of slope failures and the calculation of temporal probability. However, the former requires continuous landslide inventory for a substantial long period of time while the latter has problems with parameterization, which makes their application problematic over larger areas (Frattini et al., 2004; Kuriakose et al., 2009a). Therefore, a different approach is needed for estimating temporal probability where landslide information is incomplete and where landslides are first-time failures. One possibility is to use the rainfall threshold combined with the frequency analysis of the triggering rainfall for estimating the temporal probability (Lee and Jones, 2004; Cascini et al., 2005; Floris and Bozzano, 2008).

- The lack of a uniform methodology for the assessment of the vulnerability of element at risk is another problem in quantitative risk analysis (Glade and Crozier, 2005). This is further complicated if elements at risk are both movable (different types of vehicles and commuters) as well as stationary (alignments and buildings). Very few examples in literatures...
are available on the vulnerability assessment of different types of movable and stationary elements due to landslides of different sizes. There are no established landslide vulnerability curves for different types of elements at risk. The lack of research on vulnerability is probably due to the scarcity of good damage records and therefore, in most studies, the assessment of vulnerability remains somewhat subjective (Dai et al., 2002).

- The concept of landslide risk analysis is well documented and several publications are available (e.g., Dai et al., 2002; Fell et al., 2008), but the number of publications on quantitative landslide risk estimation in specific cases is still rather modest. The problem here appears much related to the insufficient landslide and damage information, and the inherent difficulties in estimating hazard and uncertainties associated with the risk analysis (van Westen et al., 2006). Uncertainties in the risk analysis are inevitable because the input parameters themselves contain a high degree of uncertainties (Carrara et al., 1992; Stern and Fineberg, 1996; Bell and Glade, 2004). However, risks can be expressed in a quantitative term (e.g., as annualized loss) by incorporating uncertainties in the analysis itself and providing results with a range of values.

- The ultimate goal of a landslide risk analysis is to reduce risk to the society. If the results are not applied for societal benefit or the models are not accepted by the society then the ultimate objective of risk analysis fails. Although some attempts have been made to model landslide risk only a very few have actually specified their application in the risk reduction planning. In fact landslide risk assessment is still in a developing stage (Glade et al., 2005). Even in more developed countries, methods for landslide risk assessment are not fully implemented except for Hong Kong (GEO, 1999) and Australia (AGS, 2000) which have their own standardized landslide risk assessment programme. Also in India, though landslide studies have been carried out for many years there are only few cases where the results are applied in planning risk reduction strategies. The main reason is the insufficient adaptation of the scientific output of the models to the needs of the end users, which find it difficult to understand. Since landslide risk analysis is a new subject in India, therefore efforts are needed first to understand end users’ perception to landslide risk and then present results in a way that the society can understand, accept and utilise it in reducing risk to life and properties.

### 1.2 Motivation for research

Prior to 2001, the disaster management in India was mostly focusing on post disaster relief and rehabilitation. Only after the devastating 2001 Bhuj earthquake, the disaster management focus shifted from post disaster relief
centered approach to a more proactive one that integrates disaster mitigation into developmental planning. For landslide disasters, the Geological Survey of India was declared as the nodal agency for landslide hazard and risk studies in India. Subsequently, the Indian government targeted a total of 10,000 kilometers of roads connecting different hill towns and pilgrimage sites for landslide hazard and risk assessment on scales ranging from 1:25,000 or 1:50,000.

To assess landslide risk along these roads we require landslide inventories of sufficiently long period of time. The fastest approach to prepare such inventories is to use aerial photographs of multiple periods. However, aerial photographs for past dates are either not available for all targeted areas or their usage is prohibited due to security reasons.

Besides problems related to the data availability, India also lacks expertise in landslide risk analysis and in fact there is no publication related to landslide risk assessment in India (NDMA, 2009).

Given the above facts and the research problems discussed in Section 1.1, the following aspects motivated me to carry out this research: (i) the necessity of exploring data sources other than remote sensing for landslide inventory mapping along transportation corridors, (ii) establishing a methodology for landslide hazard and risk analysis, and (iii) developing expertise on landslide risk estimation in India. This research focuses on the use of historical records in landslide inventory mapping and in quantifying landslide hazard and risk based on these data. The research was undertaken under a joint collaboration project of the Geological Survey of India (GSI), National Remote Sensing Centre (NRSC) in India and Faculty of Geo-information Science and Earth Observation (ITC), University of Twente in The Netherlands.

1.3 Research questions

Given the problems stated in Section 1.1 and the motivation discussed in Section 1.2, in this research I intend to address the following questions:

1) Can railway/road maintenance and technical records be used to generate a landslide inventory that indicates the location, date of occurrence and volume of landslides over a substantially large time period?

2) Can these records be used to:
   - Analyze the spatial probability of landslide occurrence using frequency statistics,
Introduction

- Analyze the temporal probability of landslide occurrence using rainfall-threshold analysis,
- Analyze the landslide size probability using the volume information for specific triggering events.
3) Which method is suitable for the quantification of landslide hazard for the purpose of risk analysis and land use planning along transportation corridors?
4) Can the landslide inventory derived from maintenance records along transportation lines be used to make a prediction of the landslide hazard on the natural slopes above and below these lines?
5) Can the historic landslide information be used for establishing vulnerability curves for the railway, road, vehicles and people?
6) Which method can provide a reasonable estimate of direct and indirect risks along transportation corridors? What are the sources of uncertainties in the risk analysis?
7) Can the result of risk analysis be used to manage landslide risk along transportation corridors?

1.4 Research objectives

In order to find feasible solutions to the proposed problems, I intended to explore historical records as a cost-effective means of landslide inventory mapping. The aim is to extract landslide information from the available historical records and to convert them into a spatio-temporal landslide inventory, and to develop methods to apply this information for the quantification of landslide hazard and risk along transportation lines.

Thus, the specific objectives of the research are:

1) To develop an approach to prepare a landslide inventory based on historical information,
2) To develop methods of quantifying landslide hazard along transportation corridors for the purpose of risk analysis and land use planning, which include:
   • a method for estimating (temporal) probability of occurrence of landslides using information on triggering events and landslide occurrence dates,
   • a magnitude-frequency relationship of rainfall-induced landslides.
3) To assess the vulnerability of movable and stationary elements at risk for landslides of different sizes,
4) To develop methods to quantify direct and indirect risks along transportation corridors,
Chapter 1

5) To highlight the application of quantitative landslide hazard and risk information in planning risk reduction strategies.

1.5 Thesis outline

The thesis deals with landslide risk quantification along transportation corridors based on historical information. To quantify risk several components are also analyzed, such as landslide hazard, rainfall thresholds, size-frequency relation, vulnerability of elements at risk, etc. Therefore, the thesis is organized into chapters that address these specific topics, the related problems, review of relevant literature, methodology and results followed by discussion and conclusions. The relation between different chapters within a broader framework of Landslide Risk Management, adapted from Fell et al. (2005), is summarized in Figure 1.2.

Following this Introduction (Chapter 1), Chapter 2 describes the study area where the research was conducted. General information on landslides and the type of damage caused is provided along with the geo-environmental conditions, including geomorphology and geology, land use and rainfall characteristics. The chapter also specifies the relevance of selecting the study area for this research and provides a summary of previous landslide susceptibility work carried out in the Nilgiri area.

Chapter 3 provides details of the landslide inventory obtained from historical information. The chapter presents the organizations involved in collecting landslide data and the structure of different types of data sources, their data format, and the type of data along with examples. Some of the limitations and sources of uncertainties are also discussed. Finally, the characteristics of the obtained landslide inventory are presented and the completeness of the record is evaluated.

Chapter 4 provides the result of the analysis of the landslide inventory. The relationship between landslides and rainfall are presented, and an estimate of the (temporal) probability of occurrence of landslide triggering events is made. The chapter also provides statistics of landslide size, and discusses its relation with other factors. The majority of this chapter was published as Jaiswal and van Westen (2009) and Jaiswal et al. (2011a).
Chapter 5 discusses the analysis of landslide hazard. Separate models are presented for the hazard analysis on cut slopes along the transportation lines and for natural slopes. For natural slopes, two approaches are presented: the first uses a rainfall threshold-based temporal probability for the analysis of hazard, and the second uses a relationship between cut slope and natural slope failures for the calculation of landslide hazard. Most of this chapter have been published as Jaiswal et al. (2010b) and Jaiswal et al. (2011a).
Chapter 6 presents the results of the landslide risk analysis along transportation corridor. After a brief review of the relevant literature, an approach to estimate both direct and indirect risk along the transportation corridor is presented. The chapter shows the usefulness of historical data in estimating landslide risks along the road and the railroad, including: (i) the direct risk to the infrastructural properties, moving vehicles and commuters, and (ii) the indirect risk due to the traffic disruption. On the natural slopes above and below the transportation lines, direct risk is estimated to elements at risk located in the initiation areas of potential landslides and in the run-out path of landslides by incorporating run-out distance in the risk analysis. Most of this chapter has been published as Jaiswal et al. (2010a) and Jaiswal et al. (2011b).

Chapter 7 provides validation of the developed models. The chapter presents details on the landslide events of November 2009, including the rainfall and the type of damage caused. It also accounts experiences of people who witnessed the landslide events in 2009. The 2008 and 2009 landslide events were used to validate the rainfall threshold model, the landslide size probability model, the susceptibility model, and the hazard and risk models.

Chapter 8 presents the various options for using hazard and risk information in risk reduction strategies. For emergency preparedness the perception of the local Nilgiri communities towards landslide risk is evaluated and simplified maps are generated for the benefit and understanding of end users. A rainfall threshold-based early warning system is presented, which could be used in risk awareness programmes involving public participation. The chapter also presented the use of quantitative hazard and risk information for the planning of structural measures, and for spatial planning and zoning indicating areas where the landslide hazard is too high for planning future developments. Most of this chapter is based on Jaiswal et al. (2011c).

Chapter 9 reflects on the research objectives, conclusions are drawn and general recommendations are proposed related to the data format for collection of landslide data, the landslide hazard and risk analysis, and the landslide risk reduction. Finally, topics for future work in continuation of this research are provided.

The following papers related to this research have been published in international peer-reviewed journals:

Introduction

Chapter 2: Study area

The term ‘transportation corridor’ generally refers to a tract of land containing at least one main line for transport such as a road or a railroad. In this study the transportation corridor refers to a 22 km² area encompassing a 24 km long section of a road and a 17 km long section of a railroad (Figure 2.1). The corridor forms a part of Coimbatore and Nilgiri districts of the western Tamilnadu region in southern India and falls within the Survey of India toposheet no 58 A/15. The road is a national highway (NH-67) and the railroad is declared by UNESCO as a "world heritage railway route". Both form part of the main transportation lines connecting Mettupalayam to Coonoor in the state of Tamilnadu (Figure 2.1).

This study area is selected because of (i) its significance for the scope of this work, (ii) the quality and abundance of historical landslide data, (iii) the availability of a good network of rain gauges with daily rainfall data, and (iv) the availability of landslide damage information.

This chapter presents some of the characteristics of the study area that are relevant for the research. For the area, general information on landslides, the type of damage caused and on the local setting, including geomorphology and geology, land use and rainfall characteristics will be presented. A summary of the previous landslide susceptibility mapping carried out in the Nilgiri area will also be presented.

2.1 Geomorphology and Geology

Nilgiri (meaning Blue Mountains) is the name given to a range of mountains panning across the states of Tamilnadu and Kerala in southern India. They are part of the larger Western Ghats mountain chain making up the western edge of the Deccan Plateau. The Nilgiri hills, rising from the lowlands of Coimbatore, represent a plateau with an elevation around 2,400 m above the surrounding plains. It slopes steeply into the Mysore plateau towards the north and merges gradually with the Western Ghats in the north-west, west and south-west. It is bounded by the Bhavani River in the south and Moyar River in the north. The plateau has a length of 55 km and width of 32 km and approximately occupies an area of 1,800 km².
Two different types of landforms have been identified in the Nilgiri plateau. One type contains high peaks and rocky escarpments and is marked by radial drainage patterns. These landforms are termed as Doddabetta landforms (Parthasaradhi and Vaidhyanathan, 1974). The other landforms include the plateau with gentle topography with thick soil development, and meandering streams, which are locally termed as Ootacamund landforms (Sehsagiri and Badrinarayanan, 1982).

Within the study area, the Nilgiri plateau has steep slopes to the south, and gentle slopes to the north and near ridge tops. It forms a part of the Coonoor River basin with the ridge connection Tiger Hill and Kori Betta to the north and Coonoor River to the south. The area has an elevation difference of 1,641 m with lowest areas near Kallar farm (400 m) and highest at Kori Betta ridge (2,041 m) (Figure 2.1). The area has two distinct geomorphic features, namely moderately dissected plateau to the west of Marapallam and highly
dissected slopes to the east of Marapallam (Sehsagiri and Badrinarayan, 1982). The drainage pattern in the area is mostly sub-dentritic.

Geologically, the area exposes charnockite rocks and garnetiferrous quartzofelspathic gneisses belonging to the Charnockite Group of Archaean age (Seshagiri and Badrinarayanan, 1982). These are overlain by lateritic soils. Outcrops are well exposed in escarpment slopes and along cut slopes of the road, railroad and landslide scarps. These rocks are light bluish grey in colour and medium to coarse grained. The charnockites in most places show only crude foliation on fresh surfaces, which become more prominent upon weathering. The regional strike of the foliation is ranging from ENE-WSW to E-W directions with moderate to steep dips. The sub-tropical climate and intense physical and chemical weathering have resulted in a thick yellowish to reddish brown soil. The overburden thickness (including weathered zone) varies from less than a meter to about 32 m (Seshagiri and Badrinarayanan, 1982).

2.2 Land use

The Nilgiri hills are characterised by a variety of land uses, including agriculture, tea plantations, forest plantations, spice plantations, reserved forests, residential areas, waste land, roads, railroads, etc. Forest and tea plantations are the main land use types. Almost 56% of the total area in the Nilgiri district is covered by forest. Out of the remaining area, 70% is under tea and coffee cultivation.

Settlements in the Nilgiri have expanded particularly in the latter half of 20th Century. The population in the entire Nilgiri district has increased from 112,000 in 1901 to 762,000 in 2001 (Census Abstract, 2001). The changes in the size of the residential areas remained small i.e., from 685 km² in 1961 to 742 km² in 2001 although the number of residential houses has increased from 82,174 in 1961 to 182,682 in 2001 (Census Abstract, 2001). At present almost all settlements in the district are connected by all weather roads.

In the actual study area, which has a size of 22 km², tea plantation forms the main land use type, located mostly on gentle slopes. The steeper slopes are covered by forest. Figure 2.2 shows the percentage distribution of different land use types within the study area. Forest is categorized as ‘reserve forest’ and covers about 59% (Figure 2.2A). There are only a few settlements, with Burliyar, Gandhipuran and Katteri as the major residential settlements while other residential units are within tea estates (Figure 6.3).
Settlements cover about 1.2% (0.26 km²) of the area. The percentage distribution of different types of buildings is shown in Figure 2.2B. Out of a total of 1,272 buildings, 90.5 % (1,152 buildings) are residential. Shops constitute 4.9% (63 buildings) of the total buildings and are mostly located along the road (NH-67) in Burliyar and Katteri. Offices (27 buildings) and tea factories (6 buildings) are located within the tea estates and cover around 3% of the total buildings. Other building types individually constitute less than 1% of the total buildings.

Population data was obtained from a field survey carried out in 2008. The total population is 6,784 people residing within the study area. These includes 1,479 families consisting of 2,675 young males (13-60 years), 78 old males (> 60 years), 2,582 young females, 84 old females and 1,365 children (< 12 years). Most (88%) of the household heads are manual workers engaged in the tea and horticulture (spice garden and plant nursery) plantation. Their average income is less than US$ 100 per month.

2.3 Rainfall characteristics

The Nilgiri hills receive most of its rainfall during both the south-west (SW) monsoon and the north-east (NE) monsoon. The SW monsoon starts in the month of June and extends up to August whereas the NE monsoon starts in October and extends up to December. The area around Coonoor receives more rainfall during the NE monsoon. Based on data from 1935 to 2006, the minimum, mean and maximum annual rainfall around Coonoor was 914 mm, 1,671 mm and 2,953 mm, respectively. During the same period, the average monthly rainfall during October to December was 855 mm whereas during June to August it was 225 mm.
Figure 2.3 shows the variation in rainfall during the five years period from 2002 to 2006 as measured in the rain gauges located at Coonoor (western part of the study area), Hillgrove (central part) and Kallar farm (eastern part of the study area). The figure indicates that the average total rainfall between April and August is uniform throughout the study area, but between October and December it shows a slight decrease in the central part. The average annual rainfall recorded at Coonoor and Kallar is 1,939.4 and 1,853.2 mm, respectively and the difference from west to east is 86.2 mm. The lowest recorded annual rainfall is 750 mm and the highest is 3,165 mm in these rain gauges.

The number of days with recorded rainfall also varies, depending on the season and the area. The total number of days with recorded rainfall in October to December is less than that in April to August, particularly in Coonoor and Hillgrove area but even then the winter rainfall contributes approximately 50% to the total annual rainfall (Figure 2.3). This period also contributes about 38% of the total rainfall days. The maximum rainfall recorded in a single day between October and December is twice as much as between April and August. The maximum daily rainfall varies from 49 to 245 mm.

In the above analysis (Figure 2.3) the period of summer rain is taken from April to August instead of June to August (SW monsoon). This is because sporadic incidences of rainfall-induced landslides have also been reported during April and May before onset of the SW monsoon.

Based on the frequency distribution of monthly rainfall for the period between 1925 and 1979 Seshagiri and Badrinarayanan (1982) showed that in Coonoor about 85% of the months have monthly rainfall \( \leq 280 \) mm, 15% \( \leq 40 \) mm, and 15% have very high rainfall in the range of 280 to 850 mm. The months with very high rainfall are mostly between October and December where rainfall is due to the NE monsoon.

### 2.4 Past landslides and loss

Landslides are very common events in the Nilgiri area, which occur mostly as debris slides or debris flows triggered by high intensity or prolonged rainfall. Historically landslides have resulted in numerous losses of lives and properties. Seshagiri and Badrinarayanan (1982) provided a brief description of some of the past landslide events.

The earliest landslide record pertains to the “Avalanche” landslide, which occurred in 1824 due to a heavy rainfall lasting for eight days. In 1881, the...
Coonoor road (NH-67) and Kotagiri-Mettupalayam road were damaged by landslides triggered by high rainfall. In 1891, about 740 mm rainfall within few days triggered many landslides along the Kotagiri-Mettupalayam road, which resulted in the closure of the road for 21 days. In October 1905, about 170 mm of rain triggered numerous landslides around Coonoor, which resulted in loss of life and property. In 1978 and 1979 high rainfall triggered numerous landslides in the Nilgiri hills, which resulted in casualties and immense damage to properties and environment. The unprecedented rains triggered about a hundred landslides in 1978 and nearly 200 landslides in 1979.

Along the railroad, landslide investigation reports date back to 1920s. Rao (1927) investigated some of the landslides along the railroad. The author attributed slope cutting made for the railroad alignment as the main cause for landslides. He also recommended monitoring of cut slopes during heavy rains for timely forecasting of landslides. At present the railway department incur an annual loss of about US$ 217,000, which includes loss resulting from the physical damage of the infrastructures by landslides, loss from the blockage of the railroad and the railway operational loss.

2.5 Previous work on landslide susceptibility

The first detailed and systematic investigation of landslides in the Nilgiri district was the preparation of a macro scale (1:50,000) landslide susceptibility map covering 250 km² area. The project was initiated in 1979 by the Geological Survey of India in collaboration with the State Geology Branch, Government of Tamil Nadu (Seshagiri and Badrinarayanan, 1982).
Chapter 2

The project was taken after the devastating landslide events of 1978 and 1979. The studies included landslide inventory mapping by photo-interpretation using 1:10,000 colour infra-red aerial photos, detailed mapping of the major landslides, determination of soil properties, preparation of thematic maps using aerial photos and field surveys, and preparation of a qualitative landslide susceptibility map of the Nilgiri hills.

Based on the photo-interpretation studies, landslides were classified into two age groups: old and recent. About 300 landslide scars were identified from the photographs and most of them were classified as debris slides. Four thematic maps, namely slope (six classes), soil thickness (four classes), drainage (eight classes) and land use (seven classes) were considered for the susceptibility analysis, and weights were assigned based on the frequency of landslides in each thematic class. The final susceptibility map was classified into five landslide susceptible zones.

The susceptibility study showed that the maximum percentage of landslides were distributed within slopes ranging 15° to 25° (47% landslides), soil thickness > 30 m (52% landslides), sub-dendritic drainage pattern (54% landslides) and land use, namely cultivated lands and tea plantation containing 34% of landslides in each category. The study also revealed that both steep as well as gentle slopes have failed during 1978 and 1979 landslide event. The study indicates that the landslides of 1978 occurred on comparatively steeper slopes (25° to 30°) than those of 1979. The synthesis of this correlation with rainfall data revealed that the intensity of precipitation in 1978 was high only for three days, whereas the rainfall in 1979 was distributed between August and December, the period between 11 and 22 November 1979 being the wettest. This indicates that the 1978 slides occurred due to heavy precipitation in a short period, when there were flash floods, and consequent saturation of the slopes resulting in mass movement over relatively steeper slopes. On the contrary, during the 1979 monsoon the longer duration of rain period permitted greater infiltration of water into soils and triggering of landslides in areas as gentle as 10° slope due to pore water pressure (Seshagiri and Badrinarayanan, 1982). The obtained landslide susceptibility map (Figure 2.4) shows the entire Coonoor area in zone V (very high susceptibility) and part of the transportation corridor in zone III (moderate) and zone II (low susceptibility).

The report of Nilgiri landslides (Seshagiri and Badrinarayanan, 1982) provided useful information on the type of landslides triggered during 1978 and 1979, their spatial distribution (shown as points) and their relation with different environmental factors. Figure 2.4 shows the spatial distribution of
Study area

landsides triggered in 1979 within the study area. In 1978, most landslides triggered to the west of the study area (around Ootacamund) and in 1979, most landslides occurred around Coonoor. In the report the authors mentioned that in 1979 numerous landslides occurred along the road and the railroad between Kallar and Coonoor, however they could not spatially map them from the 10,000 scale aerial photos. This could be because of the presence of thick canopy cover along the road and the railroad and the size of landslides being smaller than the mapping scale of the aerial photos.

Figure 2.4 Part of the landslide susceptibility map of the Nilgiri hills (Seshagiri and Badrinarayanan, 1982).
Chapter 3: Landslide inventory

Mapping and characterisation of landslides are essential for landslide hazard and risk analysis. The generation of a landslide inventory is a tedious work as landslides occur individually and have to be identified, mapped and inventoried one by one (van Westen et al., 2006). Landslide inventories contain basic information about landslides such as location, classification, morphology, volume, run-out distance, activity and date of occurrence/activity (Wieczorek, 1984; Fell et al., 2008). Inventories are prepared using different techniques depending on the scope of the work, the extent of the study area, the scales of base maps, the quality and detail of the accessible information, and the resources available to carry out the work (Guzzetti et al., 2000).

In this chapter the methodology used for preparing a landslide inventory from historical records is presented. The type of organizations involved in maintaining landslide data, the data format and some key limitations of inventory mapping are discussed. Finally, the characteristics of the obtained landslide inventory are presented and the completeness of the record is evaluated.

3.1 Introduction

Landslides leave discernible signs on slopes, most of which can be recognized, classified and mapped in the field or from photo-interpretation (Varnes, 1978; Hansen, 1984). These signatures are mostly visible as morphological changes such as changes in slope type, breaks in slopes, hummocky surfaces, etc. These morphological signs can be interpreted by experts to determine important landslide information such as type of failure, the rate of movement, the surface area, the volume and the run-out distance.

Identification of landslides becomes difficult if the morphological signatures are altered. This could be due to several reasons, including natural ones such as growth of vegetation or successive landsliding, and anthropogenic such as modification of slope for stability or removal of landslide deposit. In areas where land cover change is very fast even large landslides become indiscernible within a short period of time. Figure 3.1 shows an example from the study area where a landslide scar, covering 15,000 m², is almost indiscernible within 14 years due to the rapid growth of vegetation. Landslide deposits along roads or railroads are often immediately removed during clearance or rescue (Corominas and Moya, 2008).
Landslide inventories can be prepared through various methods (e.g., Wieczorek, 1984; Hansen, 1984; Guzzetti et al., 2000; Devoli et al., 2007; van Westen et al., 2008) such as detailed geomorphologic fieldwork, mapping from remote sensing data and topographic maps, historical archive studies and interviews. Due to the lack of sufficient historical information on landslides, stereoscopic interpretation of aerial photographs or satellite images from the past is often used as the main source for obtaining a multi-temporal landslide inventory (Rib and Liang, 1978). The large-scale inventories are compiled through the interpretation of medium and large scale aerial photographs, supplemented by field checks. Mapping of landslides from aerial photographs is a convenient, fast and efficient way of preparing landslide inventories, however the method has certain drawbacks. In densely forested regions identification and measurement of landslides by remote sensing is hampered by the forest canopy so that smaller landslides are difficult to map and are generally overlooked (Brardinoni et al., 2003). Besides difficulties in identifying small landslides there is also a problem of assigning age to the mapped landslide. The age of a landslide is generally taken relative to the date of acquisition of the remote sensing data. Due to the lack of data on the exact date of occurrence of landslides such inventories are unsuitable for analyzing the relationship between landslides and triggering events (van Westen et al., 2006).

In spite of the above limitations, inventories at a catchment scale covering large area are commonly prepared using aerial photos or high resolution satellite data. However, for a small area e.g., a small river basin or along transportation corridors historical records can provide vital information for landslide inventory mapping. In fact, the importance of historical records in
landslide inventory mapping has been long recognized (Glade, 2001). Many researchers have prepared landslide inventories using historical records such as technical reports, newspapers, internet, historical archives and local information from population (e.g., Guzzetti et al., 1994; Glade and Crozier, 1996; Glade, 2001; Devoli et al., 2007). Such inventories provide important information such as date of occurrence, volume of displaced material and damage caused, which otherwise are difficult to infer. Besides having certain advantages, historical inventories also have some limitations. Most often historical records are incomplete as they contain information on only those landslides that have caused damage, e.g., to the population (Salvati et al., 2003). Another problem remains with the availability and the accessibility of good records.

Irrespective of the method used the ultimate objective of an inventory mapping is to generate a good quality and a substantially complete landslide inventory. The inventory should contain all landslides that occurred in an area within the considered time period. Historical records containing information on all landslides triggered in an area are seldom available, except for those available in some technical offices, such as road and railway maintenance units or geotechnical units, which produce inventories containing continuous records of landslide occurrences (Fell et al., 1996). Most often such inventories only refer to landslides from cut slopes and fills along transportation corridors and since these are prepared shortly after the occurrence of a landslide-triggering event therefore they record most of the landslides triggered by the event. Such inventories, if available, can be a good source of landslide information and can be used to obtain a substantially complete landslide inventory at least along transportation corridors.

Since the present research focuses on landslide hazard and risk analysis along transportation corridors, therefore an attempt was made to use historical records available with the geotechnical and railway maintenance units to prepare a multi-temporal landslide inventory. In the next section, the historical data sources and types of information available in the records will be described.

### 3.2 Historical data sources and types of information

In the Nilgiri area, landslide investigation is a multi-disciplinary work involving several organizations at different levels. Major landslide investigations are carried out by technical organizations, which submit
Landslide inventory reports to the local authorities. Investigations are either for slope treatment measures, for building infrastructures, or for susceptibility mapping needed for planning purposes. Small landslides along the railroad are investigated by railway authorities. Each organization is a custodian of their landslide records, and has their own rules and restrictions on data sharing.

Preparation of the landslide inventory commenced with the search of historical data sources. Four organizations were identified where historical data were available. Based on the type of information, the data sources are grouped into three main categories:

- **Railway maintenance register**: The first continuous record of landslides along the railroad was available from railway maintenance registers (locally called ‘railway slip register’). Since 1 January 1992, data were present in an analog (paper) form recorded in a register and maintained by the Southern Railway office at Coonoor. The railway slip register is updated soon after the occurrence of a landslide triggering event and is used for tendering contracts for railroad clearance. It contains data on the spatial distribution of landslide debris on the railroad. An example of the type of data available in the register along with a photograph of the register is shown in Figure 3.2. The location of landslides is referenced in three levels. The first level gives the location with respect to the two railway stations such as QLR-ONR (i.e., between Kallar and Coonoor). The second level denotes the nearest kilometer (km) number marked on the railroad, and the third gives the location with respect to the nearest telephone posts (e.g., TP 2 and TP 3), which are also permanently marked on the railroad. The average distance between two telephone posts is 50 m. The landslide description contains the type of material (e.g., earth mixed with boulder), total volume of debris on the railroad and its date of occurrence. The slip register also provides additional information on damages and date of restoration of the railroad for traffic.

- **Railroad landslide table**: Another data source available with the Southern Railway office at Coonoor was a summary table of landslides along the railroad. From 1 January 1987 to 31 December 1991, data were recorded in a graph sheet and provide the spatial distribution of landslide debris on the railroad in different months. Landslides prior to 1987 were recorded in the graph form but older records were not traceable in the railway office for the study area. An example of the type of data available in the summary table along with a photograph of the graph sheet is shown in Figure 3.3. The location of landslides is referenced with respect to the nearest telephone post and the bounding kilometer numbers. The record does not contain data on the date of occurrence of landslide, type of
material involved and total volume of debris on the railroad. It only provides the location of landslides as well as month and year of landslide occurrence.

- **Technical reports**: The technical reports include published and unpublished technical documents of landslide investigations. They were available at different places such as the Geotechnical office at Coonoor, the Geological Survey of India and the highway office. Most of the reports contained detailed geotechnical investigation of major landslides in the Nilgiri area. The reports also include field photographs of some landslides. Some reports contain an inventory of landslides along the road (NH-67). The oldest inventory was recorded in the year 1987. Prior to this year, no systematic inventory was available in the technical offices. All reports provide some basic information on landslides but the type of information varies depending on the purpose of the investigation, and the time and resources that were available. Publications on landslides in the Nilgiri area (e.g., Seshagiri and Badrinarayanan, 1982; Ramasamy et al., 2003) provided detailed information on landslides that occurred during 1978 and 1979, including their spatial distribution, detail maps of major landslides, field photographs, cause of landslides, rainfall characteristics, information on soil depth, etc.

### 3.3 Method used for inventory mapping

The data available in the historical records need to be converted into landslide information before they can be used in landslide hazard and risk assessment. The ideal method is through extensive field work coupled with participatory mapping.

Once the data sources (Section 3.2) were identified, relevant data pertaining to the landslides in the study area were compiled. After compilation, the data were rearranged based on the location description. This formed the basis for field mapping where all the data related to one specific location were listed in a tabular form. A systematic and detailed field check was then carried out. GPS was used for mapping landslides in the field but due to the thick canopy cover it did not always work properly. All landslide sites compiled from the historic archives were visited in order to identify the landslide scars based on the description provided in the historical records. The data on the landslide volume was used to infer the size of landslides. The morphological signatures left by landslides on slopes were used to identify the shape of landslides. Some of the landslide scars and run-out areas were not clearly discernable due to the vegetation cover and removal of debris and remedial works. To overcome this, five criteria were adopted for the identification of landslides
Landslide inventory

(Figure 3.4): (1) changes in the slope morphology characterized by slope concavity, surface irregularities, or hummocky terrain; (2) presence of scarp faces with contrast in vegetation cover with the surrounding areas; (3) presence of old retaining walls or other slope stabilization structures; (4) presence of removed old debris on the downslope part; and (5) information from local people. During the field work, local knowledge from residents was incorporated for locating the landslides mentioned in the historical records and landslides on natural slopes that were not in the records. For example, during the field mapping, an old worker from the railway office helped in locating older landslides mentioned in the railway slip register based on the clearance work that he had carried out. Besides locating landslides, local residents were also interviewed and questions were asked pertaining to their livelihood, physical status, family details, and any information regarding landslide damages.

<table>
<thead>
<tr>
<th>Data format</th>
<th>Railway slip register</th>
</tr>
</thead>
<tbody>
<tr>
<td>Serial Number</td>
<td>77</td>
</tr>
<tr>
<td>Date of occurrence</td>
<td>07.11.2001</td>
</tr>
<tr>
<td>Between stations</td>
<td>QLR-ONR</td>
</tr>
<tr>
<td>Kilometer</td>
<td>13</td>
</tr>
<tr>
<td>Telephone Post</td>
<td>2,3</td>
</tr>
<tr>
<td>Detail of slide</td>
<td>Earth + boulder</td>
</tr>
<tr>
<td>Volume of earth</td>
<td>1200 m³</td>
</tr>
<tr>
<td>Volume of boulder</td>
<td>100 m³</td>
</tr>
<tr>
<td>Extent of damage</td>
<td>3 rails, 10 rack bars</td>
</tr>
<tr>
<td>Date of restoration</td>
<td>Traffic restored on 26.11.2001</td>
</tr>
<tr>
<td>Remarks</td>
<td></td>
</tr>
</tbody>
</table>

Figure 3.2 Type of data present in the railway slip register.
Figure 3.3 Type of data recorded in graph sheet (referred as railroad landslide table). Red boxes denote landslide debris on the given location of the railroad.

After identifying their location landslides were then mapped on a 1:10,000 scale topographic map. Their initiation (source) and run-out area were separately marked. The morphological parameters (landslide scar length, width and depth) were plotted after carefully measuring them in the field using a meter tape. Additional data such as landslide type, run-out distance, present land use, regolith thickness, probable cause, and damage details were also added to the inventory. The availability of detailed maps and field photographs of some landslides on natural slopes facilitated in identifying the shape of landslide scars and run-out areas (e.g., Figure 3.1). The volume of mapped landslides was recalculated by multiplying the morphological parameters. The mapped landslides were digitized as polygons or points and entered in a geo-database of ArcGIS. Separate layers were prepared for the landslides associated with cut slopes and natural slopes. The smaller landslides were digitized as points in a separate layer. A unique identification number (ID) was assigned to each landslide (polygon or point), which provided a link between the spatial and non-spatial attributes. The type of landslide information obtained after the field check along with an example is shown in Figure 3.5.
3.4 **Source of errors, limitations and uncertainty in inventory mapping**

The reliability of historical inventories depends largely on the quality and abundance of the data sources, and type of data therein (Guzzetti et al., 1994; Glade, 2001). Uncertainty is induced in the inventory map if landslides are not described correctly in historical records. If description of a landslide contains all necessary information such as landslide morphology, type, location, and size, and accompanied by photographs or maps then the identification of the landslide is easy and mapping is subjected to very little error. Some technical records contained detailed description of the landslides along with illustrations and field photographs but for others, including the
railway slip register the volume was used to infer the size of landslides. The railway slip register provides the volume that remains on the railroad and does not provide any information on initiation volumes. For a small landslide where all its material is accumulated on the railroad, the recorded volume is a good indication of the landslide size. Where data on volume is incomplete then other indications/proxies (Figure 3.4) were used to identify landslide with a higher uncertainty. In case of the unavailability of data on volume (e.g., from the railroad landslide table), the record was only used for obtaining the number of landslides per section of the (rail) road and not for spatially mapping of landslide scars.

Errors can also occur due to the unconventional way of data recording, for example, in technical reports the location of some of the landslides along the road was described based on culvert number, which was often found to have changed due to the successive road alterations, and at some places landslide widths were measured as the length of retaining walls. The incomplete data on volume or unconventional description of landslide morphology resulted in a rather high uncertainty in mapping old landslides particularly if their morphological signature is altered or obliterated.

Persistence of landslide morphology within the landscape is very important if the landslide inventory mapping is based on historical records. The historical records provide either a description of the area where landslides occurred or the location which was affected by debris. In any case one has to infer the spatial location of landslide scars based on details given in the records and has to use the morphological signature on hill slopes to accurately locate landslides. Thus, the persistence of landslide morphology within the landscape is very important for identification and mapping of landslides. Even after carrying an exhaustive and detailed field work, I could locate only 67% of the historical landslides mentioned in railway slip registers and technical reports. The other 33% were not recognizable in the field even though their locations and other details were known.

Once a landslide is recognized in the field it must be mapped on a topographic base map. Since the boundary coordinates of a landslide are not available, the topographical and morphological features shown on the base map were used to locate the landslide. Significant mapping errors can occur if the morphology of the terrain in not clearly identifiable for the given scale map, if the landslide is not very distinct or if the information on the map, such as road and railroad alignment, land use boundaries, shape of divides and drainage lines, are not accurately shown on the base map.
3.5 **Summary statistics of the landslide inventory**

In total 932 landslides were obtained from the historical records covering a 21-years period from 1987 to 2007 along the transportation corridor. Out of these 578 landslides (62%) were obtained from the railway slip register (from 1992 to 2007), 220 (24%) from the railroad landslide table (from 1987 to 1991) and 134 (14%) from technical reports (from 1987 to 2007). Through field mapping it was possible to identify and map 67% of the compiled landslides of the railway slip register and technical reports. Some of the smaller landslides with a volume less than 20 m$^3$ were not identifiable in the field due to possible reactivations which have obliterated the earlier morphology. The volume of these small landslides was therefore taken directly from the original source data. Since they were small and located along the road or the railroad, it was presumed that most of the released material from these landslides was accumulated on the road and the railroad. Therefore, the measured volume from the maintenance records was considered a good representation of the size of these landslides.

Figure 3.6 shows the annual distribution of recorded landslides. Landslides occur annually (except in 1995) with an average rate of 44 landslides per year. Major landslide activities were observed during 1987, 1992, 2001 and 2006. In terms of the monthly distribution of recorded landslides, November is the severest month (Figure 3.7) containing 54% of the landslides. This month also receives the highest rainfall each year due to the retreating monsoon.

![Figure 3.6 Annual distribution of the recorded landslides.](image_url)
Figure 3.7 Monthly distributions of the recorded landslides.

The landslide map is shown in Figure 3.8. Landslides were classified as either ‘debris slide’ or ‘debris flowslide’ following the classification proposed by Cruden and Varnes (1996). Landslides initiating as slide and then converting to flow under saturated condition are grouped under ‘debris flowslide’. Out of the recorded 932 landslides, about 99% are debris slides. Most of these landslides are shallow translational with a depth of the slip plane less than 5 meters. Only three landslides had a depth more than 5 meters. The landslides are further grouped into cut slope and natural slope failures based on the location of their source area. The location of the toe of the rupture determined whether a landslide was classified as having occurred on natural slopes or cut slopes. In total 901 landslides (97%) are recorded on cut slopes and only 31 landslides (3%) have occurred on natural slopes. All landslides on natural slopes occurred as first-time failures. Smaller landslides on the cut slopes are found to have a short run-out as the road and the railroad provided a horizontal base for accumulation of the debris.

In terms of the volume most of the landslides (92%) lie within the range of 2 to 500 m$^3$. Only 6% of the landslides have a volume in the range of 501 to 1,500 m$^3$ and the remaining 2% have $>1,500$ m$^3$ to a maximum of 150,000 m$^3$. The statistics of landslide volume is based on the landslide inventory obtained from the railway slip register and technical reports.

3.5.1 Landslide characteristics along the railroad

To the east of Marapallam the railroad is cut through steep slopes covered by forest and to the west it transects through gentle slopes covered by tea estates. Most of the landslides affecting the railroad originate from cut slopes, which are left unsupported and become prone to failure during rains. Table 3.1 summarizes the main characteristics of landslides on cut slopes. The inventory from the railroad landslide table is not added in the statistics.
shown in Table 3.1 because of the unavailability of data on volumes. The average density is 33 landslides per kilometer length of the railroad but, in some sections, the density of slope failures is higher, exceeding 50 landslides per kilometer.

![Landslide inventory map](image)

**Figure 3.8 Landslide inventory map.** In box A: landslide source areas are shown in black and run-out areas in grey colour.

All mapped landslides are debris slides triggered by rainfall. The slid material mostly consists of overburden lateritic soils mixed with debris of weathered gneissic rock. Failures are common during rains when the exposed overburden mass resting on the cut slopes slips downslope. Such failures are common due to the build-up of pore water pressure on the contact (Iverson, 2000). Figure 3.9 shows examples of debris slides along the railroad. The landslides are small (average volume ~90 m³) but occur in large number and cause substantial damage to the railway. Figure 3.9C shows an example of debris slides that occurred on 14 November 2006 and which affected the railway tunnel portal and completely damaged the railway track. Workers engaged in the track restoration work are also seen in the figure. In 2006, few landslides also occurred on natural slopes above the railroad. Figure 3.9A shows an example of one such landslide on a natural slope, which initiated at the head of a stream and the debris followed the stream course down slope passing underneath the railway bridge.
Table 3.1 Main characteristics of landslide inventory along the railroad, road and on natural slopes.

<table>
<thead>
<tr>
<th>Attributes</th>
<th>Railroad</th>
<th>Road</th>
<th>Natural slopes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of landslides</td>
<td>nr</td>
<td>565</td>
<td>116</td>
</tr>
<tr>
<td>Volume of smallest landslide</td>
<td>m$^3$</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Volume of largest landslide</td>
<td>m$^3$</td>
<td>3,600</td>
<td>5,250</td>
</tr>
<tr>
<td>Average volume of landslides</td>
<td>m$^3$</td>
<td>90</td>
<td>360</td>
</tr>
<tr>
<td>Median volume of landslides</td>
<td>m$^3$</td>
<td>20</td>
<td>160</td>
</tr>
<tr>
<td>Standard deviation of landslide volume</td>
<td>m$^3$</td>
<td>270</td>
<td>700</td>
</tr>
<tr>
<td>Average landslide density</td>
<td></td>
<td>33/km</td>
<td>4/km</td>
</tr>
</tbody>
</table>

Figure 3.9 Examples of landslides along the railroad. (A) debris slide above the railroad located on a natural slope along a stream, (B) debris slide on cut slope along the railroad and (C) railway track completely damaged by debris slides from cut slopes. Black arrow indicates position of the railway track which was completely damaged.

Figure 3.10 shows the spatial distribution of mapped landslides along the railroad in different years from 1992 to 2007. Due to the small size the location of landslide scars is represented as points. The minimum number of landslides recorded was in 1994 (5 landslides) and the maximum in 2006 (119 landslides). The figure indicates that the spatial distribution of landslides is not uniform every year except in 1992, 1996, 2001 and 2004 when landslides occurred all along the railroad. More landslides are located towards the eastern part of the study area, which is probably due to steep slopes.
Figure 3.10 Spatial distribution of landslides in different years from 1992 to 2007 along the railroad. Points represent location of landslide scars on cut slopes. In 1995 no landslides occurred.
3.5.2 Landslide characteristics along the road

The road (NH-67) runs almost parallel to the railroad but at lower altitude. It transects through forest and tea estates with gentler slopes than the railroad. Landslides along the road are mostly debris slides originating from cut slopes and triggered by rainfall. Table 3.1 summarizes the main characteristics of landslides on cut slopes. Between 1987 and 2007, a total 116 landslides were reported on cut slopes. The spatial distribution of mapped landslides is shown in Figure 3.8. The average density is 4 landslides per kilometer length of the road but, in some sections, the density of slope failures is higher, exceeding 10 landslides per kilometer.

Figure 3.11 shows examples of debris slides along the road. In most cases landslides did not cause major damage to the road structure. Small landslides are particularly less damaging as they have very short run-out and most of the material remains at the toe of the slide (Figure 3.11A). Landslides of slightly larger size (e.g., Figure 3.11B to D) are more damaging particularly resulting in the temporal blockage of the road and disruption of traffic.

3.5.3 Landslide characteristics on natural slopes

Also on natural slopes landslides are triggered by rainfall and occur mostly as first-time failures. Figure 3.12 shows examples of debris slides on natural slopes and Table 3.1 summarizes their main characteristics. Between 1987 and 2007, a total of 31 landslides were reported. Major events were recorded in 1987, 1993, 1996 and 2006. In 2006, 197 landslides (141 on cut slopes and 11 on natural slopes) occurred within the study area. Out the 11 landslides on natural slopes, 7 were smaller than 1,000 m$^3$, 3 were between 1,000 and 10,000 m$^3$ and one was more than 10,000 m$^3$. The landslide map is shown in Figure 3.8. Smaller landslides with volumes less than 100 m$^3$ occur mostly as overbank failures along the first and second order drainages due to removal of the toe by torrent streams (Figure 3.12B). Larger landslides occur as shallow and deep translational failures (Figure 3.12C). Most of the casualties and property damages (plantation areas and buildings) are attributed to larger landslides. In the study area, the largest recorded landslide is located near Marapallam (Figure 3.1). The Marapallam debris flowslide was triggered due to extreme rainfall on 11 November 1993 on steep slopes covered by forest. The rainfall was recorded as 310 mm in a rain gauge located on the Tiger hill. The estimated volume at the source is approximately 150,000 m$^3$ and debris flowed to the distance of more than 700 m up to the Coonoor River.
Landslide inventory

Figure 3.11 Examples of landslides on cut slopes along the road (see text for explanation).

Figure 3.12 Type of landslides on natural slopes (see text for explanation).
3.6 Evaluation of triggering events

Event-based inventories are prepared just after a prominent triggering event which depicts all slope failures caused by that particular triggering event in an area (Guzzetti et al., 2004). Landslide inventories of a larger period of time can be used to extract specific event-based inventories, which provide information on the location and types of failures in an area, linked to the same triggering event. Figure 3.13 shows an example of a series of landslide events on a cut slope near Katteri. The old scar belongs to the 1979 event and within that smaller landslide scars have developed in 2006 and 2007.

![Figure 3.13 Temporal evolution of landslides near Katteri. (A) is the field photograph and (B) is the illustration showing different landslide scars.](image)

For the period 1987 to 2007, a total of 111 landslide event dates were obtained from the historical records. The term "landslide event" is used hereafter for days when one or more landslides were triggered by rainfall. Out of 111 events, actual date was only known for 87 events. For 24 events the month of occurrence was available (taken from the railroad landslide table). It is assumed that in the latter case only one event had occurred each month. Table 3.2 provides the main characteristics of all landslide events that have affected the area in the period from 1987 to 2007. The number of
Landslide inventory

landsides per event varies from one to 166 and the number of events per year varies from one to 11.

Out of these 111 events, landslide data of only seven events were available from the technical reports and the rest were taken from the railway maintenance records. Since the railway maintenance record is purposely meant for tendering contract for debris clearance and is updated soon after each landslide triggering event it, therefore, records all landslides triggered by an event. The presence of data on a substantial fraction of small landslides (median volume ~20 m$^3$; Table 3.1) and the availability of a record of 111 events in 21 years time (average ~5.2 events/year), including events that triggered even one landslides clearly indicates that the event inventories along the railroad are substantially complete at least for the time period from 1987 to 2007.

In contrast, technical reports provided information on seven events that affected the road and natural slopes. From the description given in some of the technical reports it is evident that only few events that resulted in small landslides along the road are not recorded as they did not cause any damage. For two events (i.e., 14 December 1987 and 14 November 2006) a more detailed investigation was carried out and therefore a substantially complete inventory was available for these two dates.

The biggest event was recorded on 14 November 2006 when 166 landslides were triggered by high rainfall measuring 150 mm in three hours. Landslides occurred on cut slopes along the railroad and road, and on natural slopes. Immediately after the event, the railway office at Coonoor collected landslide data along the railroad and recorded them in the railway slip register. The geotechnical office at Coonoor made an inventory along the road (NH-67) and on natural slopes, and presented the data in the form of a technical report. In January 2007, a field work was carried out and the 2006 inventory was updated. Landslides that occurred in uninhabited areas were also included, thus making the 2006 event inventory substantially complete.

Out of 166 landslides, most (148) occurred on cut slopes along the railroad and road, and 18 occurred on natural slopes. The majority of landslides occurred east of Burliyar where rainfall was higher. The largest recorded landslide was a debris flowslide east of Kallar farm (see box in Figure 3.8, and Figure 3.12 C and D). The Kallar landslide with a source volume of 16,000 m$^3$ flowed over a distance of 250 m destroying part of horticulture properties and the road. Casualties due to the November 2006 event were not severe except one person died and three injured, and one lorry got
damaged. However, landslides caused substantial losses to the railway and road properties, and horticulture plantations.

Table 3.2 Main landslide triggering events in the period 1987 to 2007.

<table>
<thead>
<tr>
<th>Event Year</th>
<th>Event date and number of landslides</th>
<th>Total slide (#)</th>
<th>Landslide volume</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Date/month (#)</td>
<td></td>
<td>Min. (m³)</td>
</tr>
<tr>
<td>1987¹</td>
<td>Oct (23), Nov (19); Dec (36); 14/12 (43)</td>
<td>121⁴</td>
<td>50⁴</td>
</tr>
<tr>
<td>1988¹</td>
<td>Sept (1); Nov (2); Dec (1)</td>
<td>04</td>
<td>--</td>
</tr>
<tr>
<td>1989¹</td>
<td>Feb (1); March (1); Jul (1); Sept (3); Oct (1); Nov (22); Dec (2)</td>
<td>31</td>
<td>--</td>
</tr>
<tr>
<td>1990¹</td>
<td>Jan (5); Feb (1); March (3); Oct (29); Nov (10)</td>
<td>48</td>
<td>--</td>
</tr>
<tr>
<td>1991¹</td>
<td>Jan (6); Apr (1); May (3); July (1); Oct (2); Nov (46)</td>
<td>59</td>
<td>--</td>
</tr>
<tr>
<td>1992</td>
<td>14/11 (8); 15/11 (27); 16/11 (17); 20/11 (3); 21/11 (14)</td>
<td>69</td>
<td>6</td>
</tr>
<tr>
<td>1993</td>
<td>10/11 (6); 11/11 (27)</td>
<td>33</td>
<td>10</td>
</tr>
<tr>
<td>1994</td>
<td>11/11 (5)</td>
<td>05</td>
<td>2</td>
</tr>
<tr>
<td>1995</td>
<td>No event</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>1996</td>
<td>17/12 (41)</td>
<td>41</td>
<td>2</td>
</tr>
<tr>
<td>1997</td>
<td>3/7 (1); 11/7 (1); 16/10 (1); 10/11 (1); 27/11 (16)</td>
<td>20</td>
<td>6</td>
</tr>
<tr>
<td>1998</td>
<td>8/1 (1); 18/8 (1); 27/9 (1); 9/10 (2); 13/10 (3); 9/11 (2); 2/12 (16); 11/12 (5); 12/12 (1)</td>
<td>30</td>
<td>3</td>
</tr>
<tr>
<td>1999</td>
<td>8/2 (1); 14/4 (1); 16/8 (1); 2/9 (1); 8/10 (1); 16/10 (23); 6/11 (4); 23/11 (2); 24/11 (1); 29/11 (2)</td>
<td>34</td>
<td>2</td>
</tr>
<tr>
<td>2000</td>
<td>25/9 (1); 14/11 (1); 15/11 (2); 22/11 (1); 24/11 (3); 1/17 (2); 31/17 (1)</td>
<td>27</td>
<td>2</td>
</tr>
<tr>
<td>2001</td>
<td>1/1 (1); 31/7 (1); 25/10 (1); 26/10 (3); 27/10 (22); 16/11 (4); 17/11 (26); 23/11 (3); 24/11 (1); 25/12 (13); 27/12 (7)</td>
<td>82</td>
<td>2</td>
</tr>
<tr>
<td>2002</td>
<td>5/5 (1); 8/10 (19); 2/11 (2); 5/11 (12)</td>
<td>34</td>
<td>4</td>
</tr>
<tr>
<td>2003</td>
<td>20/3 (1); 30/4 (1); 13/5 (1); 20/5 (1); 19/8 (1); 10/11 (1)</td>
<td>06</td>
<td>2</td>
</tr>
<tr>
<td>2004</td>
<td>5/5 (21); 17/10 (1); 20/10 (3); 22/10 (4); 30/10 (1); 2/11 (3); 7/11 (2); 9/11 (6); 13/11 (2)</td>
<td>56</td>
<td>5</td>
</tr>
<tr>
<td>2005</td>
<td>7/10 (4); 22/10 (1); 7/11 (2); 13/11 (3); 9/5/11 (6)</td>
<td>16</td>
<td>2</td>
</tr>
<tr>
<td>2006</td>
<td>17/10 (4); 18/10 (9); 21/10 (2); 22/10 (5); 2/11 (8); 4/11 (2); 13/11 (1); 14/11 (166)</td>
<td>197</td>
<td>3</td>
</tr>
<tr>
<td>2007</td>
<td>8/4 (7); 28/5 (1); 27/10 (11)</td>
<td>19</td>
<td>2</td>
</tr>
</tbody>
</table>

Total: 932

¹ data based on technical report pertaining landslide inventory along the road.
² out of 121 landslides 78 slides are taken from the railway landslide table for which volume is not known.
³ Landslides data taken from the railway landslide table that only contains information on the number and month of occurrence of landslide (month (#)).
Table 3.3 compares characteristics of landslides on cut slopes along the railroad and road triggered by the 14 November 2006 event. The percentage distribution of landslide volume in different volume classes is similar though the total number of landslides is more along the railroad than the road. The average size of landslides along the road is larger than along the railroad.

### Table 3.3 Characteristics of landslides on cut slopes triggered by 14 November 2006 event along the railroad and the road.

<table>
<thead>
<tr>
<th>Attributes</th>
<th>Along railroad</th>
<th>Along road</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of landslides</td>
<td>nr 88</td>
<td>60</td>
</tr>
<tr>
<td>Total volume of landslides</td>
<td>m³ 22,400</td>
<td>20,100</td>
</tr>
<tr>
<td>Volume of smallest landslide</td>
<td>m³ 7</td>
<td>2</td>
</tr>
<tr>
<td>Volume of largest landslide</td>
<td>m³ 2,400</td>
<td>5,000</td>
</tr>
<tr>
<td>Average volume of landslides</td>
<td>m³ 260</td>
<td>340</td>
</tr>
<tr>
<td>Median volume of landslides</td>
<td>m³ 130</td>
<td>140</td>
</tr>
<tr>
<td>Standard deviation of landslide volume</td>
<td>m³ 380</td>
<td>700</td>
</tr>
<tr>
<td>Percentage of landslides ≤100 m³</td>
<td>% 41</td>
<td>41</td>
</tr>
<tr>
<td>Percentage of landslides 101 – 1,000 m³</td>
<td>% 55</td>
<td>52</td>
</tr>
<tr>
<td>Percentage of landslides &gt; 1,000 m³</td>
<td>% 4</td>
<td>7</td>
</tr>
</tbody>
</table>

### 3.7 Discussion and conclusions

Landslide risk assessment requires information on the spatial and temporal distribution of all landslides and of all sizes affected an area within the considered time period. Historical records are the ideal source of such information, provided they are available and accessible. As a limitation all historical records are not reliable and most often they are not complete, for example, newspapers only record those landslides that caused substantial damages to life and property, and in many cases different newspaper sources provide conflicting information on the same landslide event (Devoli et al., 2007).

In this case, the railway maintenance records and the technical reports on landslides were found to be very suitable for obtaining a multi-temporal landslide inventory along the transportation corridor, at least for the period from 1987 to 2007. Particularly, the railway slip register and the railroad landslide table were the most important data source for estimating temporal frequency of landslides because they contain continuous records of all landslides along the railroad. The railroad landslide table, lacked information on volume and the exact date of occurrence of landslides. Among the three data sources (see Section 3.2), the quality of landslide information was better in the technical reports because they were prepared by geologists and were purposely meant for the landslide work. However, such reports are not made frequently.
The landslide inventory map (Figure 3.8) shows large areas without landslides and some areas with a high concentration of landslides (e.g., west of Buriyar). The areas with no landslide are either actual landslide free areas with no history of landsliding such as the plateau area to the north of the railroad, or areas where past landslides have been overlooked in the landslide mapping. Many of the landslides in the inventory were mapped along the railroad and road where the information was substantially complete.

Earlier researchers have also tried to map landslides in the Nilgiri area using high resolution aerial photographs, for example Sehsagiri and Badrinarayan (1982) have mapped 300 landslides triggered during 1978 and 1979 using 1:10,000 scale colour infra-red aerial photos. Out of the 300 landslides, only 2.25% i.e., less than 10 slides were mapped along different roads and railroad within the Nilgiri hills. In the report the authors mentioned that “innumerable” landslides occurred along the road between Mettupalayam and Coonoor during 1979. The description given in the report and landslide map clearly indicate that many of the landslides along the road were not mapped, which could be due to the thick canopy cover or the size of landslides being smaller than the mapping resolution. Although the report contained detailed information on major landslides that occurred during 1978 and 1979 within 250 km² of the Nilgiri hills but due to the lack of information on the location, size and morphometry of landslides pertaining to the study area these events were not included in the present analysis. Attempts were also made to identify landslides triggered in 2006 within the study area from a high resolution (2.5 m) pan chromatic stereo Cartosat-1 data of 24 April 2007. I could identify only 48 of the 197 landslides triggered in 2006. This is because most of the landslides were small (average volume < 400 m³) and located along the road and the railroad transecting through the forested areas.

The landslides in the study area are relatively small in size in comparison to the known mass movements in the Nilgiri hills, such as those shown in Seshagiri and Badrinarayanan (1982). Some landslides are of volume less than 5 m³. One could argue that small slides are actually local slips which may not be of much significance. This could be true if such slides are on natural slopes but along a road or a railroad even small slips can be disastrous, resulting in road accidents or train derailment. The inventory suggest that most (92%) of the landslides are of volume less than 500 m³. Small landslides in fact constitute most part of landslide inventories, particularly if inventories contain cut slope failures as well. For example, out of the 5,000 landslides reported in the Geotechnical Engineering Office (GEO) database of Hong Kong for the period from 1984 to 1997, 69% are related to cut slope failures and out of the 2,811 landslides in the GEO database for the
period from 1992 to 1997 about 90% are of volume less than 50 m$^3$ (Dai and Lee, 2001).

From the study it can be concluded that historical records are the most important source of landslide information, particularly for small slope failures along transportation corridors and for areas where other data sources are not available. The records provided valuable data on the date of occurrence, location and size, and gave information on socio-economic implication, which are otherwise difficult to obtain. Of course, limitations and possible errors related with the data collection, evaluation of the sources, and data interpretation need to be recognized. The study shows that at least 33% of the landslides may not leave any recognizable indications in the terrain, which gives a good indication of the possible incompleteness of inventories that are made only based on image interpretation and fieldwork.

Good quality event inventories should be substantially complete. A functional definition of completeness requires that the landslide inventory should include a substantial fraction of all landslides at all scales and importantly it must include a substantial fraction of the smallest landslides (Malamud et al., 2004). The completeness of event inventories depends on many factors, important being (i) the purpose for which inventory is being prepared and (ii) the mapping scale or the resolution of data used. If the purpose of the inventory is to access damage to life and property, then often landslides around settlements are inventoried or if the mapping scale is smaller than the landslide itself then generally small landslides are overlooked, thereby resulting in incompleteness of the event inventory. In literature there is no unique measure of completeness of an inventory, however an inventory of ‘fresh’ landslides can be substantially complete if detailed mapping has been carried out shortly after the landslide triggering event (Malamud et al., 2004), such as the railway slip register.

In summary it can be concluded that the landslide inventory contains all the landslide events that occurred in the period from 1987 to 2007, and also nearly all landslides that occurred during this period, including the small ones (< 20 m$^3$) especially along the railroad. Care was taken to make sure that landslides are not counted twice by carefully checking the recorded landslides in the field. Most landslides are individually small in size and repeatedly affect cut slopes. In fact very large sized landslides with recurrence period more than the time series are not present on cut slopes, at least in this part of the study section.
Chapter 4: Analysis of temporal and size probability

A landslide inventory obtained from historical records can be used to perform a number of steps needed in landslide risk assessment, including: (i) estimating the temporal probability of occurrence of landslide events; (ii) estimating the size probability of landslide; (iii) estimating the spatial probability; and (iv) determining the vulnerability of elements at risk.

In this chapter two of these components will be presented: temporal and size probability. First, a study is made of rainfall-thresholds, which are used to estimate the temporal probability of occurrence of landslide events. Secondly, the frequency-size relationship of landslides will be analysed and an estimate of probability of landslide size will be made.

Other analysis including hazard and risk will be discussed in detail in the subsequent chapters. The relationship between landslides and rainfall will later help to ascertain landslide hazard and to develop a landslide early warning system.

4.1 Assessing the temporal probability of landslide events

Landslides in the study area are rainfall induced and therefore an indication of the temporal probability of landsliding can be obtained by evaluating the temporal probability of the rainfall events themselves combined with an analysis of the rainfall-thresholds, which is the minimum intensity or duration of rainfall required to trigger a landslide (White et al., 1996; Crozier, 1997; Reichenbach et al., 1998). Such an analysis requires information on the actual dates of occurrence of landslides and corresponding rainfall data, which in this case were obtained from historical records. The assumption is that the rate of landslide triggering events and landslide occurrence will remain the same in future under the given geo-environmental conditions, which can be questionable when taken into account the combined effects of global changes, related to climate and land use. The temporal probability of landsliding can also be estimated using the mean rate of landslide occurrences (e.g., Coe et al., 2000, 2004; Guzzetti et al., 2005). The results of such studies are generally only applicable to the modelled area.

Rainfall thresholds for landslide initiation can be estimated either using physically-based or empirical methods. The physically-based threshold models use local terrain characteristics (e.g., slope gradient, soil depth, and
Temporal and size probability

lithology) in a dynamic hydrological model in which rainfall is the most important variable (Wilson and Wieczorek, 1995; Crosta, 1998; Terlien, 1998; Montgomery et al., 1998). These models are less suitable for larger areas as they require detailed information on parameters (e.g., soil properties, changes in groundwater level, discharge conditions), which are difficult to extrapolate outside the instrumented (with piezometers, tensiometers, etc.) test sites. Empirical methods are based on the estimation of rainfall thresholds obtained by studying rainfall conditions that have resulted in landslides. They are usually contained in envelope curves based on variables such as cumulative rainfall, antecedent rainfall, rainfall intensity, and rainfall duration (Caine, 1980; Wieczorek, 1987; Glade, 1998; Crozier, 1999; Chleborad, 2000; Crosta and Frattini, 2003; Aleotti, 2004; Giannecchini, 2005; Chen et al., 2006; Jakob et al., 2006). The most commonly used empirical model is based on the rainfall intensity and duration. This threshold model requires data with high quality and temporal resolution (at least hourly rainfall data), which are not frequently available. Other models based on antecedent rainfall work with daily rainfall data, which are relatively simple and inexpensive to measure over large areas.

In next sections, I propose a method to determine the temporal probability for landslide events using the probability of exceedance of an empirically derived rainfall threshold and the probability of occurrence of landslides related to the rainfall threshold.

4.1.1 Rainfall distribution

Daily rainfall data were collected from 14 rain gauges belonging to the tea estates (eight stations), the horticulture department (three stations) and the railway office (three stations). The distribution of the rain gauges is shown in Figure 4.1. All gauges are non-automated tipping bucket type. Everyday readings are taken in the morning hours (08.30 hrs). Daily rainfall data from the three rain gauges of the railway office were analysed to know the variation in the rainfall pattern from west to east in the study area (see Section 2.3). Although there is not much variation in total annual rainfall from west to east, there is a large variation in rainfall during the landslide triggering events. Figure 4.2 shows the rainfall variation for representative landslide events measured at six rain gauges. The events considered for this analysis had resulted in more than 20 landslides in different parts of the study area depending on the amount of rainfall. The amount of daily rainfall on the landslide events varies considerably and Figure 4.2 shows no clear trend from west to east. Most of the landslides have occurred in areas where the rainfall was relatively high. For instance on 14 November 2006, more
than 150 mm rainfall around Hillgrove and Burliyar resulted in numerous landslides in these areas, but not in the western part of the study area.

During the investigated period, from 1 January 1987 to 31 December 2007, 87 individual landslide events with known date were differentiated (Table 3.4), of which 66 occurred in the months from October to December. These events were taken from the railway slip register and the technical reports where information on the dates of landslide was available.

**Figure 4.1** Location of sections and rain gauges for determining rainfall thresholds: 1- Coonoor, 2- Glandale, 3- Upassi, 4- Tiger hill, 5- Runneymede, 6- Katteri farm, 7- Marapallam, 8- Singara_UD, 9- Singara_LD, 10- Hillgrove, 11- Burliyar, 12- Adderley, 13- Mutteri and 14- Kallar farm. Sections I, II, III and IV are the areas used for determining rainfall thresholds. Their corresponding terrain profile is shown in boxes.
Figure 4.2 Rainfall recorded during landslide events at six rain gauge stations. Each event has triggered more than 20 landslides along the railroad.

4.1.2 Methodology for temporal probability assessment

The input of the rainfall threshold analysis is the time series of daily rainfall $R_d(t)$ in mm day$^{-1}$, where $t$ is time. For a landslide (L) to occur, the daily rainfall must exceed a threshold, which is a function $R(t)$ of the daily rainfall in a period, and of the amount of the antecedent rainfall $R_{ad}(t)$, i.e., rainfall that have occurred prior to the day of landslide occurrence.

$$R(t) = f[R_d(t), R_{ad}(t)]$$  \hspace{1cm} (4.1)

where $R_{ad}(t)$ is the antecedent rainfall in mm. This function of $R$ defines the probability of occurrence of the landslide L: $P(L)$. If $R_T$ is the threshold value of $R$ then,

$$P[L|(R > R_T)] = 1 \quad \text{and} \quad P[L|(R \leq R_T)] = 0$$  \hspace{1cm} (4.2)

Thus, in this simplified model, landslides always occur when $R$ exceeds $R_T$ and does not occur when value of $R$ is lower than or equal to $R_T$. In the former case, the probability of occurrences of landslide $P(L)$ depends on the exceedance probability of $P(R > R_T)$, i.e., $P(L) = P(R > R_T)$.

In reality, however, the threshold may be exceeded without resulting in any landslide. This may be attributed to some other factors which locally influence
the initiation of a landslide and are not fully understood (Aleotti and Chowdhury, 1999). This difference can be reduced when the final probability is viewed as the conditional probability of a given threshold exceedance $P(R > R_T)$ and the probability of occurrence of a landslide $P(L)$, given the exceedance (Lee and Jones, 2004; Floris and Bozzano, 2008). Thus, the probability of landslide occurrences can be given by the intersection of two probabilities,

$$P[(R > R_T) | L] = P(R > R_T) \times P[L | (R > R_T)]$$  (4.3)

This means that the probability of occurrence of both $(R > R_T)$ and $(L)$ is equal to the probability of $(R > R_T)$ multiplied by the probability of occurrence of $(L)$, assuming that $(R > R_T)$ has already occurred. The probability of $(R > R_T)$ can be obtained by determining the exceedance probability of the rainfall threshold and the probability of $[L | (R > R_T)]$ relies on the frequency of occurrence of landslides after the threshold has been exceeded.

The above assumption that landslide have to occur whenever a given rainfall threshold is exceeded may not hold always and everywhere. However, it is also expected that landslides will not occur below the rainfall threshold. Hence, for rainfall-triggered landslides, this assumption can be an acceptable first-approximation to work with and to estimate the frequency of landslide events by establishing relations between the landslide trigger, its magnitude and the occurrence of the landslides.

### 4.1.3 Determination of the rainfall thresholds

#### 4.1.3.1 Methodology for determining rainfall thresholds

To determine the rainfall thresholds, only shallow translational cut slope failures along the railroad were selected that occurred from 1992 to 2007 in the period from October to December. The reasons for this were: (i) the majority of landslide events have occurred between October and December, (ii) the date of all landslide events is known only for the period from 1992 to 2007, and (iii) the railway records contain information on all landslide events that occurred in the study area. Three events from 2006 and one event of 2007 were further selected for the validation of the threshold model. A threshold model based on antecedent rainfall was selected because of the availability of daily rainfall data, and also due the fact that in future recording of daily rainfall is cost effective and the model is easy to implement.

Because of the variation in the daily rainfall totals associated with landslide occurrences (Figure 4.2) and the presence of 14 rain gauges within the study area (Figure 4.1) it was important to select representative rain gauges for
establishing the landslide-rainfall relationship along the different sections of the railroad. The selection was made based on the horizontal distance and elevation difference with respect to the railroad, and also on the landslide distribution and topographical location of the rain gauges. The Burliyar rain gauge was taken as representative of the area east of Burliyar since it is located on the same elevation and topographic situation of that of the railway. The rain gauges located at Hillgrove, Katteri and Runnemede were taken as representatives of the other sections of the area.

Depending on the type of landslides and their geo-environmental setting, the number of antecedent days can vary from 3 days for shallow landslides to 30 days for deep landslides (Kim et al., 1992; Aleotti, 2004; Zezere et al., 2005; Chleborad, 2006). To determine the suitable number of antecedent days required for shallow debris slides and debris flows, 54 landslide events were selected that have occurred between 1992 and 2006 around Burliyar. These triggering events have resulted in 270 shallow landslides around this area. After analyzing the 3, 5, 15 and 30 days antecedent rainfall, according to the method suggested by Zezere et al. (2005), the 5-days antecedent rainfall was considered suitable for the analysis.

To determine $R_T$, a scatter plot was prepared showing daily rainfall against the corresponding 5-day antecedent rainfall, for each day with one or more triggered shallow landslides. The envelope curve was manually drawn such that it demarcates the lower end of the plotted points. The line can be represented by a linear mathematical equation (Crozier, 1999; Chleborad, 2000).

For the calculation of the thresholds, the transportation corridor was divided into four sections (Figure 4.1), based on topography, land use types, and terrain gradient. Rainfall conditions at each section were determined from the nearest rain gauge. Besides the rainfall threshold for the four individual sections, a general threshold was established for major landslide events that have resulted in 15 or more landslides. During the period from 1992 to 2006, the railroad has experienced 12 landslide events that have resulted in several landslides per day (from 15 to 88 failures). Such events have occurred on average once a year except in 1994, 1995, 2003 and 2005. From the 12 events only one has triggered more than 85 landslides in a day, and 11 resulted in 15 to 40 landslides. In the study area about 50% of such events have occurred when the daily rainfall was more than 100 mm and 29% when it was more than 230 mm. Such events have affected different parts of the transportation line in different years. The determination of a threshold for the individual sections was not possible, due to the paucity of data. A threshold
for the entire railroad was determined for the events that have individually resulted in 15 or more landslides.

4.1.3.2 Results of rainfall threshold analysis
The first section east of Burliyar transects through steep forested slopes. It contains 270 landslides resulting from 54 landslide events. Here $R_T$ above which a landslide can occur for the given 5-days antecedent rainfall ($R_{5ad}$) is represented by the equation $R_T = 66 - 0.93 R_{5ad}$ (Figure 4.3). The figure indicates that initially at least 50 mm of antecedent rainfall is required for a daily rainfall of 19.5 mm to initiate a landslide. When the $R_{5ad}$ is more than 75 mm, even a continuous normal monsoon is capable of triggering a landslide. The small limit of $R_{5ad}$ makes the section more susceptible to landslides.

The section west of Burliyar, around the Hillgrove, passes through steep forested slopes and moderate slopes covered by tea plantation. It contains 18 landslide events during the period from 1992 to 2006. The threshold is represented by the equation $R_T = 165 - 1.32 R_{5ad}$ (Figure 4.3). This section requires very high magnitude of daily rainfall ($R > 100$ mm) at the beginning of October to trigger a landslide. When $R_{5ad}$ exceeds 125 mm there is a possibility of getting landslides even when there is no rain.

The section of the railroad around Marapallam passes through rocky terrain, with tea plantations and forests. It is relatively less prone to landslides. During the period from 1992 to 2006, only 15 landslide events have taken place. The threshold is given by the equation $R_T = 230 - 1.32 R_{5ad}$ (Figure 4.3).

The route east of Runneymede up to Coonoor passes through gentler terrain with tea plantations and residential areas. Only at some places the cut slopes are steep and prone to landslides. This section has witnessed 22 landslide events. The threshold is represented by the equation $R_T = 250 - 1.5 R_{5ad}$ (Figure 4.3).

The general threshold for the major landslide events is given by the equation $R_T = 220 - 0.61 R_{5ad}$ (Figure 4.3). The small slope (0.61) and high intercept (220) of the envelope curve indicates that such events either require very high magnitude daily rainfall or a very high amount of five-day antecedent rainfall during the monsoon to trigger landslides.

In a few cases, landslides were also reported when no rainfall was measured on any specific day. These were the cases when high antecedent rainfall alone has resulted in landslides, due to water percolating from upslope areas. This holds for landslides associated with cut slopes because during excavation
the toe of such slopes are removed and the unsupported overburden mass becomes more prone to failure under the given condition. Thus, for all the listed thresholds, the lower boundary of the envelope curve was set to zero daily rainfall.

4.1.3.3 Validation of the threshold model
The rainfall thresholds can be used to predict the temporal probability of landslides within different parts of the study area. The use of different thresholds for different areas also provides a relative measure of the geographical distribution of terrain susceptibility (Glade, 1998). A way to test the predicting capability of the thresholds is to validate them with the control data sets, which were not used in the model.

The temporal validation of the threshold equation $R_T = 66 - 0.93R_{5ad}$ for the section east of Burliyar is shown in Figure 4.4. The validation was carried out using 2001, 2006 and 2007 rainfall, and landslide data. The 2001 and part of 2006 event data were also used in building the model. These are included here to visualise the performance or success of the model. Figure 4.4 indicates that in the period from October to December the rainfall has exceeded the threshold curve several times. Between two successive positive periods (i.e., the period for which the threshold was exceeded) there may be a period with no rainfall or very low rainfall. Each rise in the threshold curve indicates that either there is a sudden increase in the magnitude of daily rainfall.

Figure 4.3 Envelope curves for landslides. $R_T$ is the threshold rainfall and $R_{5ad}$ is the 5-days antecedent rainfall.
rainfall or there is a constant rise in five days antecedent rainfall. The width of each positive curve (or positive amplitude) denotes the period of consecutive rainy days in a given month. The crossover of the curve from negative to positive values indicates the time when the threshold is crossed and the conditions favourable for landsliding begins. One or more landslide events might be expected before the positive curve decays to the zero threshold value.

In 2001, the threshold was exceeded on four occasions and landslides were found associated with the rise in the threshold curve except for the period from 7 to 13 November (Figure 4.4). Similarly, in 2006 the threshold was exceeded on three occasions and landslides were associated with each rise. In this year the threshold was successfully validated by three landslide events that were not included in the model. In contrast to 2001, peaks of 2006 are associated with medium and low magnitude daily rainfall. For 2007 the validation is done in October. In this month, the threshold was exceeded once and it was associated with landslides (Figure 4.4). The daily rainfall in this period remained below 50 mm. The figures also indicate that landslides are not always associated with the rise in the threshold curve and at times they occur a few days after the exceedance. This could be due to the variation in the pore pressure resulting from changes in the amount of antecedent rainfall.

Similar validations were carried out for the other threshold equations: \( R_T = 165 - 1.32 R_{5ad} \), \( R_T = 250 - 1.5 R_{5ad} \) and \( R_T = 230 - 1.32 R_{5ad} \) using the 2001, 2006 and 2007 rainfall and landslide data. The analysis reveals that during October to December all the threshold curves show several positive (i.e., threshold exceedance) and negative periods (i.e., the period for which the threshold was not exceeded) except for 2007. In this year the curves did not exceed the threshold value and hence no landslides have occurred. In 2006, there was no threshold exceedance during 1 to 16 October and from 25 November to 31 December, and no landslide had occurred in these periods. Similarly, in 1995, thresholds were not exceeded in any of the rain gauges and there were no reports of landslides.

The spatial validation of the model was carried out along the 14 km long section of the railroad west of Coonoor, directly adjacent to the area where the thresholds were derived. The geo-environmental setting there is similar to the sector from Runnymede to Coonoor, and therefore the threshold equation \( R_T = 250 - 1.5 R_{5ad} \) were used for the validation. The daily rainfall data was taken from the rain gauge located at Ketty. A multi-temporal landslide inventory map was prepared from the railway slip register for this
Temporal and size probability

area as well. From the period 1992 to 2007 during October to December, 19 rainfall triggered landslide events were recognised that have individually resulted in one or more landslides. The result of the validation is shown in Figure 4.5. The figure indicates that in the years 2000, 2003, 2004, 2006 and 2007 the threshold was exceeded on a maximum of two occasions each year and occurrences of landslides are associated with each exceedance except for 2003 and 2006. In 1992, 1997, 2004 and 2006 one landslide triggering event occurred when the threshold was not exceeded, normally just one day before the threshold was reached. Because of their close proximity to the envelope curve these events are considered as the exceedance event. During the period from 1992 to 2007, the threshold was exceeded on 17 occasions and for 12 times it had led to one or more landslides. Thus, the prediction rate is 12/17 or 70%.

Figure 4.4 Validation of the threshold equation $R_T = 66 - 0.93 R_{5ad}$ for the section east of Burliyar. Validation was done for the year 2001, 2006 and 2007. Positive values on the y-axis indicate threshold exceedance ($R > R_T$). Green circles indicate the dates of landslide events considered in the model. Red circles are the event dates that were not considered in building the threshold model.

4.1.4 Determining temporal probability

The annual exceedance probability (AEP) is the estimated probability that an event of specific magnitude will be exceeded in any given year (Fell et al., 2005). For a given rain gauge AEP of the threshold $P(R > R_T)$ was determined
using a Poisson probability model. This model has been used to determine
the exceedance probability of landslides in time by, e.g., Coe et al. (2000,
2004) and Guzzetti et al. (2005). According to the Poisson model, the
exceedance probability or the probability of experiencing one or more
landslides during time $t$ is given by

$$P[N(t) \geq 1] = 1 - \exp\left(-\frac{t}{\mu}\right)$$

where $\mu$ is the mean recurrence interval between successive landslides, which
can be obtained from the multi-temporal landslide inventory data.

To determine $AEP$ of the rainfall threshold for a particular area, $R_T$ is
calculated from the threshold equation, and the result is subtracted from $R$.
Each phase of continuous positive values ($R > R_T$) is considered as the period
of maximum likelihood for landslide initiation. In this study, $AEP$ calculation
was based on the 15 years daily rainfall data from 1992 to 2006 in the
months from October to December for landslide initiation along the railroad.

![Figure 4.5 Spatial validation of the threshold equation $R_T = 250 - 1.5 R_{Sat}$ along the railroad, west of Coonoor. Bars with dark grey indicate the number of times the threshold was exceeded in a year and bars with light grey indicate the number of times that a landslide event was associated with the threshold exceedance.](image)

The next step after calculating $AEP$ of the rainfall threshold is the assessment
of the probability of landslide occurrence after the threshold has been
exceeded. The frequency can be established from the rainfall and landslide
records, for different sections of the railroad. From this frequency, the
probability of (L) conditioned on ($R > R_T$), i.e., $P[L|R > R_T]$, can be
Temporal and size probability

estimated. To achieve this, the transportation routes were further subdivided into eight smaller topographic units based on the variation in the land use type and the height of the cut slope (Figure 4.6). This was done to take account of variation in the landslide distribution in different units resulting from the unequal response of the terrain towards the threshold due to changes in local relief and land use. Other factors that play a role are differences in the height of the cut slopes and the size of the upslope area for a landslide to retrograde.

As indicated earlier, the temporal probability of landslide initiation was calculated by multiplying:

(i) \( AEP \) of the rainfall threshold, i.e., a probability of the threshold being exceeded in a year, by

(ii) the probability of landslide initiation given that the threshold is exceeded \( P[L|R > R_T]\).

In the section east of Burliyar, the threshold was exceeded 53 times in 15 years. The mean recurrence interval (\( \mu \)) between successive threshold exceedances was 15/53 or 0.28. According to Eq. (4.4), \( AEP \) of the rainfall threshold during these months is 0.97. For the other sections, according to the threshold equations given in Figure 4.3, the rainfall threshold was exceeded 29, 27, 30, and 15 times, for a section around Hillgrove, around Marapallam, east of Runnymede up to Coonoor, and for entire route, respectively. The corresponding \( AEP \) values based on Eq. (4.4) were determined as 0.85, 0.83, 0.86, and 0.63, respectively (Table 4.1).

The probability of occurrence of a landslide after the threshold has been exceeded was estimated for each topographic unit. To the East of Burliyar, \( R_T \) was exceeded 53 times in the 15 year period 1992–2006 (Table 4.1). In 17 cases, it triggered landslides in unit-I, corresponding to an estimated probability \( P[L|R > R_T]\) of 17/53 or 0.32. Similarly, in units-II and III, during the same period, landslides were triggered on 27 and 23 times giving \( P[L|R > R_T]\) of 0.51 and 0.43 respectively. Results for the other topographic units are listed in Table 4.1.

The annual temporal probabilities for different topographic units of the transportation routes for the months from October to December are given in Table 4.1 and their distribution is shown in Figure 4.6. The probability of having one or more rainfall events that can trigger landslides in any given year varies from 0.27 to 0.49. The highest probability values are assigned to the units II, III and V. These areas also have the higher incidences of reported landslides.
Chapter 4

Figure 4.6  Annual temporal probability of landsliding on cut slopes. Temporal probability is based on the exceedance probability and frequency estimates of threshold rainfall in the different units along the railroad and the road.

The 17 km railroad is represented by four thresholds which on exceedance can result in one or more landslides, in the months from October to December. The thresholds are found to vary with changes in the local terrain conditions. For the same landslide event, different areas are represented by different envelope curves. Areas west of Hillgrove are represented by an envelope curve with high slope and intercept values. These areas have gentle slopes and thus require relatively more rain to fail than the area east of Burliyar where the terrain is steep.

The rainfall-based temporal probability values that have been obtained for the railroad were used to test their applicability for the nearby road having similar terrain characteristics. The results of the prediction are shown in Figure 4.7. The frequency distribution of the recorded landslides during the period 1987 to 2007 indicates that more than 60% of the landslides have occurred within the road sectors with high temporal probability of occurrence (> 0.40) and 7% in the zones with the lowest probability value (0.27).
Figure 4.7 Frequency distribution of landslides along the road in different temporal probability classes.

Table 4.1 Temporal probability of landslide events along different units of the railroad.

| Area          | Units | Threshold equation | Number of expected landslides | Number of times the threshold exceeded | Frequency of landslide in units | Temporal probability P[R>R_l] x P[L|R_l] |
|---------------|-------|--------------------|------------------------------|---------------------------------------|------------------------------|----------------------------------------|
| East of       | I     | \( R_d = 66 - 0.93 R_{bad} \) | > 1                          | 53                                    | 0.97                         | 17                                      | 0.32                                    | 0.31                                    |
| Buriyar       | II    | \( R_d = 165 \) | > 1                          | 53                                    | 0.97                         | 27                                      | 0.51                                    | 0.49                                    |
|               | III   | \( R_d = 1.32 R_{sat} \) |                              | 29                                    | 0.85                         | 23                                      | 0.43                                    | 0.41                                    |
| Around        | IV    | \( R_d = 230 - 1.32 R_{sat} \) | > 1                          | 29                                    | 0.85                         | 14                                      | 0.48                                    | 0.40                                    |
| Hillgrove     | V     | \( R_d = 230 - 1.32 R_{sat} \) |                              | 27                                    | 0.83                         | 9                                       | 0.33                                    | 0.27                                    |
| Marapallam    | VI    | \( R_d = 220 - 0.61 R_{sat} \) | > 15                         | 15                                    | 0.63                         | 11                                      | 0.73                                    | 0.46                                    |
| West of       | VII   | \( R_d = 250 \) | > 1                          | 30                                    | 0.86                         | 11                                      | 0.36                                    | 0.31                                    |
| Runneymede    | VIII  | \( R_d = 1.5 R_{sat} \) |                              | 30                                    | 0.86                         | 12                                      | 0.40                                    | 0.34                                    |
| For Entire route | --- | \( R_d = 165 \) | | | | | | |
4.2 Classification of landslide size

It is recommended in the JTC-1 guidelines (Fell et al., 2008) that landslide hazard must also include a landslide magnitude class. Hungr (1997) argued that in literature no unique measure of landslide magnitude is available, and proposed to use landslide damage (destruction) as a measure of landslide magnitude. Damage caused by a landslide largely depends on the velocity and impact pressure of the mass, but these parameters are extremely difficult to obtain and to integrate in the hazard zoning. Therefore researchers have used only landslide area or volume as a proxy for magnitude, for certain landslide types such as slides or flows (Guzzetti et al., 2005). Crozier (2005) proposed to use multiple occurrences of regional landslide events (MORLE) as a measure of magnitude.

Among all, the most commonly used approach is based on landslide volumes. A landslide size classification based on volume was proposed by Fell (1994). He classified landslide size into seven classes with an arbitrary chosen class ranges. The smallest is of volume less than 500 m$^3$ (extremely small) and largest being more than 5,000,000 m$^3$ (extremely large). Jakob, (2005) included peak discharge and the area that will likely be inundated by landslide debris in his 10-fold classification, which also includes volcanic debris.

In this study, a landslide size classification is proposed. The landslides in the study area are grouped in four magnitude classes (Table 4.2). The variables used in this classification include landslide type, volume at source, location of scar, depth of scar, run-out distance, depth of accumulated debris, type of flow and the probability of occurrence. The classification is semi-quantitative and all variables were derived on the basis of the historical information obtained during the inventory mapping, except for the run-out and the probability, which are based on the analysis of the inventory. The details of run-out analysis are discussed in Chapter 5 and the probability in the following sections. To make the classification sufficient to conceive for the lay-person, descriptions of potential impact are also given, particularly damage potential and human perception about the risk related to landslides.

4.2.1 Landslide size definitions

Magnitude class M-I are shallow translational debris slides (volume ranging from 2 to $10^2$ m$^3$ and depth of scar < 1 m), which occur mostly from cut slopes along the railroad and the road. They occur very instantly during rainfall under saturated condition. The landslides have short run-out (< 10 m), and debris mostly get accumulated on the (rail) road with an average
Temporal and size probability

thickness of about one meter. Landslides of this class have very high probability of occurrence (probability ranging from 0.39 to 0.85) and constitute bulk of the inventory (> 50%) if they are triggered by normal rainfall. They do not cause significant damage to the road and railway structures, and no casualties have been reported. Society is generally aware of such landslides and accepts the risk as these occur frequently. If required landslides of this class can be controlled using a simple retaining structure.

Magnitude class M-II landslides occur either from the cut slopes or natural slopes (volume in the range of $10^2$ to $10^3$ m$^3$ and depth of scar < 2 m). These initiate as shallow translational debris slides and in some case may get converted into debris flowslide with a maximum run-out distance of 50 m. On the cut slopes they occur instantly under saturated condition and on the natural slopes they often initiate due to removal of the toe by streams. For those occurring from the cut slopes, only part of debris gets accumulated on the (rail) road (depth of accumulated debris ~1.5 m) and rest flows down slope. In a landslide event, more number of landslides of this class are triggered on natural slopes (53%) than those on cut slopes (13%). M-II landslides are known to have caused substantial damage to the rail and non-RCC structures. Reports of death are rare but there are reports of minor or major injuries. In general, society lives and accepts the risk. Landslides of this class are small and can be controlled using a specially designed retaining structure (e.g., retaining wall and slope treatment with soil nailing).

Magnitude class M-III includes both shallow and deep translational debris slides and debris flowslides associated with the cut and the natural slopes. Their volume ranges from $10^3$ to $10^4$ m$^3$ and have scar depth of 2 to 8 m. Debris slides of this size constitute a small fraction of total landslides triggered by an event (probability of occurrence ranging from 0.02 to 0.08). On cut slopes landslides of slightly more than half of the class size (< 6,000 m$^3$) is only reported. On natural slopes they occur as confined or unconfined high velocity flow to a run-out distance of about 200 m or even up to the gentle slopes, where debris deposits as fan with depth < 5 m. Though they occur rarely but known to have caused extensive damage to properties such as rails and buildings. Escape is possible from landslide of this size but major injuries or even death is reported in some cases. Society lives with it and tolerates risk. Landslide of this class can be controlled by specially designed retaining structures but of high cost.

Magnitude class M-IV landslides are typically debris flowslides (Volume > $10^4$ m$^3$ and scar depth of > 8 m) occurring on natural slopes. They constitute only 1% of the total landslides triggered by an event. Similar to magnitude
class III, they also occur as confined or unconfined high velocity flow but to a run-out distance of 200-1,000 m (generally up to gentle slopes) and deposit debris to a depth more than 5 m. Due to high velocity they entrain material during the flow and uproot trees along the path. Landslides of this class have caused maximum casualties in the study area. They completely damaged buildings and infrastructures, and forced for a complete resettlement. Areas with known incidences of class IV landslides are declared unsafe and no further settlements are allowed.

Table 4.2 Size classification of debris slides and debris flowslides.

<table>
<thead>
<tr>
<th>Size class</th>
<th>Type</th>
<th>Lc</th>
<th>$V_s$ range (m$^3$)</th>
<th>$S_d$ (m)</th>
<th>$R_D$ (m)</th>
<th>$A_d$ (m)</th>
<th>$P_r$ range</th>
<th>Potential consequences</th>
</tr>
</thead>
<tbody>
<tr>
<td>M-I</td>
<td>Ds</td>
<td>CS</td>
<td>$&lt; 10^2$</td>
<td>$&lt; 1$</td>
<td>$&lt; 10$</td>
<td>1</td>
<td>0.39-0.85</td>
<td>Minor or no damage to the road, rail or house; one can escape unhurt.</td>
</tr>
<tr>
<td>M-II</td>
<td>Ds; Dfs</td>
<td>CS or NS</td>
<td>$10^2$-$10^3$</td>
<td>2</td>
<td>10-50</td>
<td>$&lt; 2$</td>
<td>0.13-0.53</td>
<td>Damage rail and non-RCC structures; minor or major injuries; society accept risk.</td>
</tr>
<tr>
<td>M-III</td>
<td>Ds; Dfs</td>
<td>CS or NS</td>
<td>$10^3$-$10^4$</td>
<td>2-8</td>
<td>50-200</td>
<td>$&lt; 5$</td>
<td>0.02-0.08</td>
<td>Complete damage to rails and buildings; injuries major or even death in some cases; society lives and tolerates risk.</td>
</tr>
<tr>
<td>M-IV</td>
<td>Dfs</td>
<td>NS</td>
<td>$&gt; 10^4$</td>
<td>$&gt; 8$</td>
<td>$&gt; 200$</td>
<td>$&gt; 5$</td>
<td>0.01</td>
<td>Total damage of infrastructures and properties of all types; no reaction time and difficult to escape; devastation and death; complete resettlement and no further settlements allowed.</td>
</tr>
</tbody>
</table>

$Lc$ is location of scar, $V_s$ is the volume of landslide at source, $S_d$ is depth of scar, $R_D$ is run-out distance, $A_d$ is depth of accumulated debris, $P_r$ is probability of occurrence, Ds is debris slide, Dfs is debris flowslide, CS is cut slopes and NS is natural slopes.

4.3 Assessing the probability of landslide size

The understanding of the size-frequency relationship of landslides is of immense importance as it has implications in hazard and risk analysis (Hungr et al., 1999, 2008; Guzzetti et al., 1999, 2002; Fell et al., 2008).
Temporal and size probability

Several studies have been made on the statistics of landslide size, and probably Fujii (1969) was the first to investigate the area/volume-frequency distribution based on an inventory of 800 landslides caused by heavy rainfall in Japan. Other studies on the size-frequency statistics were based on different types of inventories, including landslides of all ages of undefined long periods of time, landslides within a defined time interval, continuous records of landslide occurrence within a region or along transportation corridors, and landslides occurring in a very short period of time such as after a rainstorm (Picarelli et al., 2005). The researchers have defined landslide size either by scarp area (Hovius et al., 1997; Stark and Hovius, 2001), by total area including the deposition zone (Guzzetti et al., 2002; Malamud et al., 2004; Guthrie and Evans, 2004), or by volume (Hungr et al., 1999; Dai and Lee, 2001; Hungr et al., 2008; Brunetti et al., 2009).

In many studies, the landslide size and frequency distribution observed to exhibit a negative power-law scaling for landslides of large size and a flattening of the curve at the lower size, termed as a "roll-over" (e.g., Stark and Hovius, 2001; Dai and Lee, 2001; Guzzetti et al., 2002; Guthrie and Evans, 2004; Malamud et al., 2004; Brardinoni and Church, 2004; Catani et al., 2005; Hungr et al., 2008). Some researchers concluded that the roll-over effect is a 'real effect' reflecting slope stability processes (Guthrie and Evans, 2004; Malamud et al., 2004), whilst others attribute it to the incompleteness of the inventory (Stark and Hovius, 2001; Brardinoni and Church, 2004; Catani et al., 2005). Inspection of literature further reveals that the frequency distribution of landslide size, particularly volume correlates also with a power-law relation for all range of volumes (e.g., Fujii, 1969; Brunetti et al., 2009). Given the above facts, it is yet not clear whether the frequency distribution of landslide size actually follows a power-law for all range of data or a roll-over distribution pattern.

If we believe that the roll-over effect is due to the incompleteness of the inventory, as demonstrated by Brardinoni and Church (2004) who have shown an increase in the frequency of small landslides when the photo-interpreted inventory was integrated by intensive field based inventory, then the actual distribution of landslide size can be established if a complete inventory is available. Since the landslide inventory obtained along the railroad, in this study, is substantially complete, it is reasonable here to use this inventory to analyze the volume-frequency relationship of landslides, at least on cut slopes along the transportation corridor.
4.3.1 Analyzing the volume-frequency relationship

To study the statistics of landslide sizes (area or volume) researchers have used the cumulative or the non-cumulative number-size distributions. Stark and Hovius (2001) suggested that a non-cumulative distribution is appropriate to observe any crossover from a non-power law to a power law scaling. In this analysis also a non-cumulative distribution was used for obtaining probability density of landslide volumes adopting the method given by Malamud et al. (2004). At first, a frequency histogram of volume was obtained at different class intervals. The frequency density was computed by normalizing the number of landslides in each bin by its width. The probability density was then obtained by further normalizing the frequency density in each bin by the total number of landslides in the inventory. The probability density $p(V_L)$ can be expressed as:

$$p(V_L) = \frac{1}{N_{LT}} \frac{\delta N_L}{\delta V_L}$$

where, $\delta N_L$ is the number of landslides with volumes between $V_L$ and $V_L + \delta V_L$, and $N_{LT}$ is total number of landslides in the inventory.

Initially all 932 landslides that occurred between 1987 and 2007 were considered for the probability density calculation. Out of these, information on volumes was available for 76%. The volume of failure varies from 2 to 150,000 m$^3$. The landslides with failure volume of less than 100 m$^3$ account for nearly 71% of the data (Figure 4.8A).

Figure 4.8B shows the probability density $p(V_L)$ of landslide volumes computed using Eq. (4.5). The observed distribution shows distinct "roll-over effect" for failure volumes less than 10 m$^3$. The linear portion of the curve with failure volumes $> 10$ m$^3$ shows has a negative power relationship with power law scaling exponent $\beta$ as 1.5 (determination coefficient $r^2 = 0.99$). The observed roll-over may be due to the fact that some small-scale landslides, particularly along the road, were not reported. Nevertheless, Figure 4.8B provides a general idea of the volume-frequency relationship of landslides in the study area.

However, in reality landslides are triggered by a specific rainfall and each landslide event differs in the total number of landslides triggered and the range of volumes (Table 3.2). Therefore, in order to understand the probability distribution of landslide volumes more accurately it is necessary to analyze each landslide event separately.
Temporal and size probability

As an example, the landslide event inventory of 14 November 2006 was used because of the availability of a substantially complete data. The inventory contains 166 landslides that affected the transportation corridor, including landslides on cut slopes and on natural slopes. Out of 166 landslides, 39% have volumes less than 100 m³ and about 45% have volumes ranging between 100 and 500 m³ (Figure 4.9A).

Figure 4.9B shows the probability density of landslide volumes for 14 November 2006 event computed using Eq. (4.5). The observed distribution shows flattening of the curve for failure volumes of less than 200 m³. This indicates that though small-scale landslides occur in relatively large number
but still not enough to follow the power law trend of the large-scale landslides (> 200 m³).

Figure 4.8B and Figure 4.9B show two different distribution curves for the same area. This implies that in both curves the probability value for a given landslide size is also different. Distribution patterns similar to Figure 4.8B and Figure 4.9B were observed in many case studies though with different values of β and the range of volumes showing power fitting. Brunetti et al. (2009) summarizes 15 case studies of the probability density distribution of landslide volumes. Out of the 15 cases, only two were for rainfall-induced debris slides, with β varying from -2.94 to -1.87, and the remaining cases were for rock failures. For the two cases of debris slides, the distribution shows roll-over for failure volumes of less than 200 m³. Dai and Lee (2001) studied the inventory belonging to the Geotechnical Engineering Office (GEO), Hong Kong consisting of 5,000 landslides (with 69% slides on cut slopes) and analyzed the cumulative frequency-volume distribution using 2,811 landslides for which information on volume was available. The distribution shows roll-over for volume less than 10 m³ and power fit with scaling exponent, α, as -0.79 for volumes ranging between 10¹ and 10⁵ m³. For the 800 landslides studied by Fujii (1969) the cumulative number-volume distribution correlated with a negative power law relation with α = 0.85. Note that for a non-cumulative power law distribution with exponent β > 1, the corresponding cumulative distribution, obtained by integration and summation, has exponent α = β⁻¹ (Guzzetti et al., 2002).

The probability density distribution shown in Figure 4.8B and Figure 4.9B thus fits well with most of the observed volume-frequency relations studied world over. In this study the availability of a substantially complete landslide inventories on cut slopes along the railroad for individual years provides us an additional opportunity to analyse the volume-frequency relation for each year separately. This will help us in understanding of the probability distribution of landslide volumes in different landslide events having different spatial distribution of landslides and different intensity of trigger (rainfall).

4.3.2 Probability density of landslide volumes in different years

Non-cumulative probability density of landslide volumes was calculated for individual years for the period from 1992 to 2007. Ideally, for such an analysis different event inventories should be analyzed, but this was not possible due to lack of a sufficient number of landslides in all events (as some events contained only one landslide). Therefore the total landslides per year were considered in the analysis. For each year probability density distribution
Temporal and size probability

curves were computed separately using Eq. (4.5). Thus, for the 15 year data (1992 to 2007) 15 curves were obtained (Figure 4.10). Inspection of the results in Figure 4.10 reveals that not all distributions shows a similar curve, rather three distinct types of distribution curves are observed (Figure 4.11):

- Type-I, where the probability density distribution of volumes shows a negative power law scaling for all range of volumes (e.g., 1993, 1994, 1997, 1998, 1999, 2001, 2002, 2003 and 2007);
- Type-II, where distribution exhibits a distinct and sharp bend of the curve (positive slope) for volume less than 30 m$^3$ (e.g., 1992, 2004 and 2005) and
- Type-III, where the distribution shows gentler flattening of the curve for volumes less than 100 m$^3$ (e.g., 1996, 2000 and 2006).

This indicates that the general nature of distribution of landslide size is not similar across all landslide events of the study area.

Table 4.3 summarizes the characteristics of the probability density distribution of volumes for each year. Differences were observed in the maximum volume of landslides in each year and the negative power scaling exponent of the fit range. The maximum volume in most of the years is between 100 and 1,000 m$^3$ except in 2003 and 2005 where the maximum volume is less than 100 m$^3$. The power exponent $\beta$ for the fit volume range varies from -0.96 to -2.4.

Although the study area is small and landslides are of the same type and triggered by the same natural phenomena under similar geo-environmental conditions (i.e., on cut slopes), but still the number of landslides and the volume-frequency distribution in each year differ. It was expected that years with a similar spatial distribution of landslides should also show identical volume-frequency relationships. However, it is not the case, for example in 1992, 1996, 2001 and 2004. Although the spatial distribution of landslides is similar in these years (Figure 3.10) the probability density distribution shows three different curves (Type-I, II and III) that differ both in the range of volumes ($10^1$ to $9 \times 10^2$ m$^3$) and in the $\beta$ value (1.4 to 2.4). Similarly, the spatial distribution of landslides in 1998, 1999 and 2002 are also comparable and although they belong to Type-I distribution pattern they differ in the range of volumes showing power fit and the corresponding $\beta$ value.
4.3.3 Effect of terrain and rainfall on the v/f distribution

The differences in the number of landslides that occurred in a year and the volume-frequency could be due to changes in the local terrain condition and the amount of rainfall, as observed by Dai and Lee (2001) in a case study of Hong Kong. The authors showed landslide volume-dependency on the intensity of rainfall and indicated that the number of landslides varies according to the rainfall intensity.

Figure 4.10 Probability density of landslide volumes for different years. $N_{LT}$ is total number of landslides in the inventory.
Temporal and size probability

Table 4.3 Characteristics of the probability density distribution of volumes of rainfall-induced debris slides $V_L$ (in m$^3$) for different years.

<table>
<thead>
<tr>
<th>Year</th>
<th>nr of slides</th>
<th>Distribution type $p(V_L)\alpha V_L^{-\beta}$</th>
<th>Volume range (in m$^3$)</th>
<th>Fit range</th>
<th>$r^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1992</td>
<td>68</td>
<td>$\beta = 1.7$ $1 \times 10^1 - 8 \times 10^2$ $2 \times 10^1 - 9 \times 10^2$</td>
<td>0.97</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1993</td>
<td>27</td>
<td>$\beta = 1.5$ $2 - 4 \times 10^3$ $2 - 4 \times 10^2$</td>
<td>0.98</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1994</td>
<td>5</td>
<td>$\beta = 0.96$ $2 - 2 \times 10^3$ $3 \times 10^1 - 2 \times 10^2$</td>
<td>0.95</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1997</td>
<td>20</td>
<td>$\beta = 1.3$ $2 - 4 \times 10^2$ $2 - 4 \times 10^1$</td>
<td>0.96</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1998</td>
<td>30</td>
<td>$\beta = 1.1$ $2 - 8 \times 10^2$ $2 - 8 \times 10^1$</td>
<td>0.98</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1999</td>
<td>34</td>
<td>$\beta = 1.4$ $2 - 9 \times 10^2$ $2 - 9 \times 10^1$</td>
<td>0.96</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2000</td>
<td>27</td>
<td>$\beta = 1.5$ $2 - 6 \times 10^2$ $3 \times 10^1 - 6 \times 10^2$</td>
<td>0.92</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2001</td>
<td>74</td>
<td>$\beta = 1.5$ $2 - 5 \times 10^2$ $2 - 5 \times 10^1$</td>
<td>0.98</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2002</td>
<td>34</td>
<td>$\beta = 1.5$ $4 - 3 \times 10^2$ $4 - 3 \times 10^1$</td>
<td>0.96</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2003</td>
<td>6</td>
<td>$\beta = 1.2$ $2 - 8 \times 10^1$ $2 \times 10^1 - 8 \times 10^1$</td>
<td>0.98</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2004</td>
<td>56</td>
<td>$\beta = 2.4$ $5 - 1 \times 10^2$ $4 \times 10^1 - 1 \times 10^2$</td>
<td>0.99</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2005</td>
<td>16</td>
<td>$\beta = 2.0$ $2 - 1 \times 10^2$ $16 - 1 \times 10^2$</td>
<td>0.95</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2006</td>
<td>119</td>
<td>$\beta = 1.8$ $3 - 3 \times 10^2$ $2 \times 10^2 - 3 \times 10^3$</td>
<td>0.98</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2007</td>
<td>9</td>
<td>$\beta = 2.1$ $6 - 2 \times 10^2$ $6 - 2 \times 10^1$</td>
<td>0.98</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 4.11 Types of curve observed in the probability density distribution of landslide volumes in different years.

To analyze the effect of the local terrain condition on the frequency distribution of landslide volumes, the entire railroad corridor was divided into four sections (Figure 4.1). For each section, a terrain profile is also prepared to highlight the general slope condition. Table 4.4 gives the terrain
characteristics of each section. These sections also have different rainfall thresholds that can trigger landslides on cut slopes (Figure 4.3). The threshold values increase from section-I to section-IV such that section-IV requires relatively large amount of rainfall to trigger landslides.

Table 4.4 Terrain characteristics along the railroad.

<table>
<thead>
<tr>
<th>Attributes</th>
<th>Section-I</th>
<th>Section-II</th>
<th>Section-III</th>
<th>Section-IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relief above the railroad before major slope break (m)</td>
<td>400</td>
<td>150 - 350</td>
<td>&lt; 100</td>
<td>&lt; 50</td>
</tr>
<tr>
<td>Average slope (°)</td>
<td>32</td>
<td>45</td>
<td>25</td>
<td>21</td>
</tr>
<tr>
<td>Overburden thickness (m)</td>
<td>1 - 10</td>
<td>1 - 10</td>
<td>1 - 10</td>
<td>&gt; 5</td>
</tr>
<tr>
<td>Land use</td>
<td>Forest</td>
<td>Barren rocks and tea plants</td>
<td>Forest and tea plants</td>
<td>Tea plants and settlements</td>
</tr>
<tr>
<td>Percent total landslides (%)</td>
<td>57</td>
<td>16</td>
<td>11</td>
<td>16</td>
</tr>
</tbody>
</table>

The cumulative percentage of total landslides within the four sections was calculated. The cumulative percentage distribution shows three distinct patterns, for example:

1. in 1992 and 1993, 26% of the landslides occurred within section-I and there is a rise in the landslide frequency towards section-IV;
2. in 1997 and 2005, a high percentage of landslides (> 85%) occurred within section-I; and
3. in 1996 and 2004, distribution of landslides is uniform in all sections.

The effect of terrain and rainfall on the volume-frequency distribution of landslides was analyzed for the three cases. The cumulative percentage distribution of landslides in the year 1992 and 1993 shows a similar trend (Pattern 1), which means that the probability density distribution of their volume should also be similar. The 1993 distribution shows a power fit for entire range of volumes while 1992 shows roll-over for small landslides. In 1992 there is a uniform rise in the percentage of landslides from section-II (20%) to section-IV (30%), whereas in 1993 there was sharp rise i.e., from 10% in section-II to 42% in section-IV indicating a sudden increase in the number of landslides in section-IV. The gentler terrain with small relief in section-IV probably resulted in more number of small landslides in 1993 thereby leading to a power distribution of landslide volumes for all range of data.

In 1997 and 2005, more than 85% landslides occurred within section-I (Pattern 2). Though both 1997 and 2005 have a similar percentage distribution of landslides along the railroad, they differ in the range of volumes and probability density curves. In 2005 the inventory contains 16
Temporal and size probability

slides with a maximum volume of 100 m³ and mean of 21 m³, and in 1997 the inventory contains 20 slides (mean = 134 m³ and maximum = 1,944 m³). The difference in the total number of landslides and the range of volumes could be due to differences in the amount of rainfall. In 25 November 2005 rainfall occurred in all sections but only in section-I rainfall was more than the threshold value ($R_d = 153$ mm and $R_{Sad} = 30$ mm). In section-III the rainfall was below the threshold value ($R_d = 139$ mm and $R_{Sad} = 6$ mm) and in section-IV it was slightly above the threshold value ($R_d = 200$ mm and $R_{Sad} = 54$ mm) but did not trigger any landslide. The rainfall on 27 November 1997 was very high in section-I with $R_{Sad} > 320$ mm and $R_d > 50$ mm. The high rainfall in 1997, which was well in excess of the required threshold value, might have resulted in more number of landslides and of relatively large volumes.

In 1996 and 2004, landslides are uniformly distributed throughout the railroad (Pattern 3) with a maximum recorded volume of 2,000 m³ and a mean of 120 m³ in 1996, and a maximum of 200 m³ and a mean of 27 m³ in 2004. In both years about 49% of landslides occurred within section-I but with different mean value and with different probability density curve. This difference was because the average daily ($R_d = 28$ mm) and antecedent rainfall ($R_{Sad} = 155$ mm) during the main event of 2004 was less than the main event of 1996 ($R_d = 155$ mm and $R_{Sad} = 334$ mm). Thus, if there is a continuous high rainfall more than the threshold value then the same terrain can trigger more landslides of large volumes.

From the above study it is evident that the number and sizes of landslides varies according to the rainfall intensity and the local terrain condition.

4.3.4 Probability of landslide volume

One of the purposes to analyze the volume-frequency distribution of landslides is to estimate the probability of landslide volume and to use the estimate in landslide hazard assessment. The probability of landslide size can be obtained from its probability density distribution by fitting a function to the curve (Stark and Hovius, 2001; Malamud et al., 2004). But due to the large variability in the frequency of landslide volume (Figure 4.10, Table 4.3), it is evident that a single probability density distribution is not enough to explain the probability of landslide sizes on cut slopes for all triggering events and hence any one curve cannot totally represent the entire study area. Since this difference was due to the variation in the intensity of landslide triggering rainfall and due to the variation in the local terrain conditions (Section 4.3.3), therefore it is appropriate to estimate probability as the
frequency percentage of landslide volumes separately for each landslide event.

Two sets of probabilities were calculated: for years with or without more than 100 landslides. This is because the event inventories indicate that if rainfall triggers less than 100 landslides in a year then the majority (> 55%) has a volume less than 100 m$^3$. These are the events that occur more frequently, have low rainfall intensity, and trigger more number of small landslides. For events resulting in more than 100 landslides (e.g., 14 November 2006), a larger proportion of consists of landslides with volumes greater than 100 m$^3$. Such events occur less frequently.

The frequency percentage of landslide size in different years was calculated, which was taken as the probability of occurrence of a particular landslide size on cut slopes (Table 4.5). The probability was calculated for each year separately and the average value was taken for further analysis. The largest landslide recorded along the railroad is of volume ~3,600 m$^3$ and along the road it is ~5,250 m$^3$.

<table>
<thead>
<tr>
<th>Landslide triggering event</th>
<th>Probability of landslide of volume $&lt; 10^2$ m$^3$</th>
<th>$10^2$ – $10^3$ m$^3$</th>
<th>$&gt; 10^3$ m$^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;100 landslides per year</td>
<td>0.5 – 1</td>
<td>0.01 - 0.33</td>
<td>0 - 0.16</td>
</tr>
<tr>
<td>(avg = 0.85)</td>
<td>(avg = 0.13)</td>
<td>(avg = 0.02)</td>
<td></td>
</tr>
<tr>
<td>≥100 landslides per year</td>
<td>0.39</td>
<td>0.53</td>
<td>0.08</td>
</tr>
</tbody>
</table>

In contrast to cut slope failures, very little information was available for landslides affecting natural slopes. Out of the total 111 landslide events, only seven events have information on landslides on natural slopes. The latest among them was 14 November 2006 event, for which a substantially complete inventory was obtained. For this event, the probability density distribution differs from the power trend for landslides with a volume < 200 m$^3$ (Figure 4.9B). The unavailability of a complete data on other event inventories affecting natural slopes makes it difficult to correlate the observed roll-over behaviour of the probability density distribution with the other event inventories similar to one carried out for the cut slopes. Not only in this study, but world over the unavailability of a substantially complete landslide event inventories at a catchment scale remains a major limiting factor in the study of landslide size distribution. Based on a handful of complete inventories, studies (e.g., Stark and Hovius, 2001; Guzzetti et al., 2002; Malamud et al., 2004; Guthrie and Evans, 2004) have demonstrated that the probability density of landslide size does not change significantly.
Temporal and size probability

with changing physiographical conditions. Malamud et al. (2004) showed that the probability density distribution are virtually identical for landslides triggered by three different triggers in three different physiographical regions (e.g., co-seismic landslides in southern California, rainfall induced landslides in Guatemala, central America and landslides due to rapid snow melting in Umbria, Italy). Besides physiographic conditions, Guzzetti et al. (2005) indicated that frequency-size statistics of landslides also does not change in time.

Similar to the cut slope failures landslide volume-dependency on the intensity of rainfall or the terrain condition cannot be tested for the natural slopes due to the paucity of data. Hence, for the probability calculation, I only considered inventory of 14 November 2006 event and assumed that in future landslide events affecting natural slopes will follow the similar volume-frequency distribution as observed in 14 November 2006.

The probability of landslide volume for natural slopes was calculated as the cumulative frequency percentage based on the data of the 14 November 2006 event and the percentage values were expressed as probability (Figure 4.12). The figure shows the probability of landslide size, i.e., the probability that a landslide will have a volume smaller than a given size $v_L$ (left axis), or the probability that a landslide will have a volume that exceeds a given size $v_L$ (right axis). The probability that a landslide can exceeds a volume of 1,000 m$^3$ and 10,000 m$^3$ is estimated as 0.07 and 0.01, respectively. I have selected only two volume category for landslides on natural slopes because of the fact that casualties are generally caused by landslides with relatively large failure volumes.

4.4 Discussion and conclusions

4.4.1 Temporal probability of landslide events

The proposed method allows to determine the temporal probability of landslide events for different sections of railroad. The model based on the rainfall thresholds allows to extend the result to the road having similar geoenvironment and rainfall conditions.
Numerous publications on regionally-derived thresholds of rainfall intensity and duration for landslides are available (e.g., Dahal and Hasegawa, 2008; Guzzetti et al., 2008; IRPI, 2009, etc.). Different climatic regions have shown different threshold values for rainfall intensities. Guzzetti et al. (2008) have attributed this to the change in morphology, soil types, and vegetation cover. Due to the lack of similar works in the neighbouring areas it was difficult to compare the present results with any established threshold of the similar geo-environment. The threshold of the Himalayan region (Dahal and Hasegawa, 2008) is to some extent comparable with our thresholds. The Himalaya initially needs high intensity of rainfall for landsliding but lesser intensity than the global threshold and when the rainfall duration exceeds four days even continuous monsoonal rainfall is capable of triggering landslides (Guzzetti et al., 2007). A similar work in Hong Kong (Lumb, 1975) for minor landslide events indicates that > 50 mm of daily rainfall is required for landsliding if 15 days antecedent rainfall is > 50 mm. This value is only comparable with the threshold for section-I with steep forested slopes. Due to the large variation in the thresholds and because of their dependency on the geo-environmental conditions, thresholds have to be developed locally for
Temporal and size probability

an area. Any attempt to use regionally-derived thresholds could lead to incorrect predictions.

In principle, each time the rainfall exceeds the threshold, it should trigger one or more landslides, but in reality this only happens with a probability ranging from 0.32 to 0.73 (Table 4.1). This means that other factors such as shear strength of the soil, topography, the saturation condition of the ground prior to the rise in the threshold curve, and successive periods of wet and dry days also influence and control the occurrence of landslides. The Poisson model is used to estimate the probability that one or more threshold will exceed in any year in a given rain gauge area. The exceeded threshold is expected to trigger shallow translational debris slides on the cut slopes anywhere within the section around the rain gauge area. Thus, the specific location (individual slope or per unit length of the railroad), number of landslides and also the size of landslides are not predicted by this model and this should be considered when interpreting the results for hazard or risk analysis. The Poisson model has been successfully tested for determining exceedance probability in spite of certain limitations and assumptions as discussed by Guzzetti et al. (2005). The assumptions such as that the mean recurrence of events will remain the same in the future as it was observed; the number of events that occur in disjoint time intervals are independent; and the probability of more than one event in a short time interval is negligible, should be considered when interpreting and using the results of the probability model. Another assumption that the rate of landslide events and landslide occurrence will remain the same in future can be questionable considering the changes in climate, land use and overburden thickness. At any given location the rate of landslide occurrence may decrease with time due to the depletion of the overburden material thus affecting the temporal probability assessment. This may be true for large landslides, however for smaller ones involving less material, such as in this case, presence of thick overburden cover facilitated repetitive failures. Also in many locations presence of a large upslope area provided space for landslides to retrograde and therefore the landslide activities persisted even though the railroad is more than 100 years old.

The thresholds show high exceedance probability varying from 0.63 for the events that can cause more than 15 landslides to 0.97 for events resulting in one or more landslides. In spite of this high annual exceedance, landslides are only triggered in 32% to 73% of the cases when the threshold is exceeded. Thus, the temporal probability of occurrence of a rainfall that can trigger landslides in any given year from October to December varies from 0.27 to 0.49. The high annual exceedance of the thresholds agrees well with
the incidences of landslides in the area. From the historical records it is evident that at least one landslide occurs every year, but the relative temporal probability of experiencing one or more landslide events depends on the local terrain and its maximum is estimated as 0.49. In this study it is assumed that within a geographic unit the rainfall may not vary significantly and thus, the temporal probability is expected to be the same in a given unit.

The model requires data on daily rainfall from a well distributed network of rain gauges combined with the actual dates of landslide occurrences. This model may not be applicable if the exact dates of landslide incidences are not known. The model was also found applicable in other nearby areas with similar geo-environment conditions. The study illustrates the importance of the use of empirical minimum rainfall threshold models for the determination of temporal probability of landslides over an area. The advantage of this approach over determination of frequency from the historical inventory of landsliding is that rainfall records are usually much longer and more complete than a historical landslide inventory. Thus, if the landslide inventory is not complete (e.g., landslides on natural slopes in this case) then the estimation of temporal probability of landslides based on threshold analysis is a better option. As a drawback this method does not provide information on the number of landslides expected and their return periods for small areas. This makes the method unsuitable for the assessment of hazard or risk for smaller sections, such as per unit length of the railroad, which requires information on the annual frequency of slope failures (AGS, 2000). However, these thresholds can be used for warning systems and landslide forecasting (Crozier, 1999).

4.4.2 Landslide size probability

The purpose of a landslide size classification is to facilitate hazard, vulnerability and risk assessment. Numerous risk scenarios are possible to generate if the hazard assessment is carried out for individual landslide size, however this will lead to a large number of outputs (e.g., risk maps), which are difficult to interpret and to plan mitigation strategies. The use of different size classes helps in reducing the quantum of outputs and generation of more meaningful maps that can be easily understood and used for planning mitigation work. The measures of size (volume) alone may not be sufficient to perceive the risk but by incorporating additional parameters such as location of landslide scar, run-out distance, depth of accumulated debris, etc. the size classification are made more meaningful for its use in the hazard and risk mitigation. The proposed four fold classification will help in interpreting the hazard map, particularly in terms of expected consequences and volume of material to be cleared from the road or the railroad.
Temporal and size probability

The parameters used in the classification of landslide size are either obtained from historical records \((V, Sd, RD, Ad)\) or based on field observation \((type, Lc)\) or derived statistically \((P)\). Since the classification is solely based on the data obtained from the study area, therefore the model may not be applicable in full to other areas having different geo-environmental conditions. Particularly the two parameters i.e., the run-out distance and the probability of occurrence may not be same in other areas because they depend largely on the characteristics of the terrain and the type of trigger \((Dai et al., 2002)\).

Analysis of the probability densities of the 15 inventories for the year 1992 to 2007 indicates that six inventories exhibit negative power law scaling of \(p(V_c)\) for landslides exceeding a threshold volume and nine inventories show negative power law distribution for all range of volumes. This observation is in accordance with the distribution pattern of landslide volumes given in Brunetti et al. (2009). The researchers have shown that irrespective of space and type of failures and their triggering mechanisms, the probability density distribution of landslide volume exhibits power law behaviour for failures exceeding a threshold volume. Inspection of other literatures reveals that contrary to the above observation the size of landslides depends on local scale of the slope (slope length) and terrain geometry \((Guzzetti et al., 2002; Hungr et al., 2008)\), and on rainfall intensity and the presence of man-made features \((Dai and Lee, 2001)\). The present findings also support to the latter theory, at least for the cut slope failures because the analysis clearly indicates that even within a small catchment area the number of landslides, the volume-frequency relationship and the range of volume varies according to the rainfall intensity and the local terrain conditions. This study confirms that landslide volumes has dependency on the local morphology and rainfall intensity, at least for cut slopes and, therefore, any attempt to use a regionally derived volume-frequency relation for estimating the probability of landslide size could lead to incorrect predictions.

Brunetti et al. (2009) studied non-cumulative distributions of landslide volumes of 19 inventories, including rock and debris slides and submarine failures. The tails of the distributions \((volume \geq 10^2 m^3)\) were shown to follow negative power laws, with \(1.0 \leq \beta \leq 1.9\), average of \(\beta = 1.3\), median 1.3 and standard deviation 0.3. In comparison to this the power law for the fit range in this study also shows variation in the \(\beta\) value (Table 4.3), with \(0.96 \leq \beta \leq 2.4\), average of \(\beta = 1.5\), median 1.5 and standard deviation 0.39. Most of the inventories correlated well with a power law distribution whilst some \((e.g., 1992, 1996, 2000 2004, 2005 and 2006)\) exhibited a roll-over of probability densities for small \(V_c\). This is similar to the roll-over identified in
the probability density distribution of landslide areas (Stark and Hovius, 2001; Guzzetti et al., 2002; Guthrie and Evans, 2004; Malamud et al., 2004; Brardinoni and Church, 2004; Catani et al., 2005). The researchers attributed the roll-over as a result of under sampling (Stark and Hovius, 2001; Brardinoni and Church, 2004; Catani et al., 2005) or a ‘real effect’ reflecting slope stability processes (Guthrie and Evans, 2004; Malamud et al., 2004). But, since the inventory along the railroad is complete I also attribute the roll-over as a ‘real effect’ and not an artefact due to sampling discrepancies.

For landslides on natural slopes I assumed that the probability distribution of landslide volumes will remain same in future as observed in 14 November 2006 (Figure 4.9B). No doubt the local variation in the terrain condition, the surface area of a slope and the overburden material can influence the volume-frequency distribution of landslides similar to one observed on cut slopes. But with the available data on natural slopes it is yet difficult to prove the dependency of volume on the terrain type considering the fact that the slope stability and triggering conditions are different on the cut and natural slopes. On cut slopes the failures are primarily anthropogenically induced. Therefore more complete event inventories are required in order to compare the characteristics of volume-frequency distribution of landslides in different natural terrain condition. However, under the given circumstances of data availability and the studies shown elsewhere (e.g, Guzzetti et al., 2002; Malamud et al., 2004), it is reasonable to assume that the probability distribution of landslide volumes on natural slopes will not vary much and will be similar to one observed during 14 November 2006, at least within this small study area.

In this research, I have used a substantially complete landslide inventory for a relatively small study area. The inventory was complete in terms of all landslides and of all sizes triggered in the study area; however it is possible that some of the ‘event inventories’ may not be complete if they have triggered landslides outside the study area. Nevertheless, for the volume-frequency analysis it is important that the inventory must record all landslides within the modelled area because the ultimate goal is to obtain the probability of landslide size for a certain study area and not for the triggers.

The probability values derived in this study is based on an inventory of a limited time period (1987 to 2007) containing less than 1,000 landslides. The probability density curves show different distribution patterns for the total inventory (Figure 4.8B) and for the individual years (Figure 4.10). It is expected that the curve would be different for an inventory covering entire Nilgiri hills. Thus, for the better understanding of the volume-frequency
Temporal and size probability

relationship we require to study more event inventories containing large number of landslides and covering large study area. Nevertheless, the study at least helped in understanding of the characteristics of debris slide volume-frequency relationship on man-made slopes along transportation corridor in a tropical country.

Based on the above analyses, I conclude that:
(i) the use of a threshold model for determining quantitative temporal probability of landslide initiation can form the basis for an improved assessment of landslide hazard over an area where continuous information on landslides is not available;
(ii) the threshold-based model may not be applicable if the exact dates of landslide incidences are not known or if the multi-temporal landslide inventory is prepared from remote sensing data where the age of landslides is relative to the date of acquisition of the data;
(iii) the frequency distribution of landslide volumes is not always the same for all landslide events within a given area;
(iv) for rainfall-induced landslides the number of landslides and the range of volumes depend on the variation in the local terrain and rainfall conditions, at least for cut slope failures therefore the estimation of the probability of landslide size based on the frequency percentage related to different magnitudes of rainfall events is a workable solution;
(v) the probability density distribution of landslide volumes can either show a negative power law distribution for all range of volumes, or can show a distinct roll-over or a flattening of curve for small volumes, and
(vi) the roll-over for small landslide volumes could be real and not an artefact due to the sampling discrepancies.
Chapter 5: Landslide hazard analysis

Landslides occur more frequently on cut slopes than on natural slopes in the study area, where the average landslide frequency is 43 slides per year on cut slopes and one slide per year on natural slopes. Therefore two different approaches are considered for the analysis of landslide hazard.

In this chapter a direct method based on landslide recurrences will be used to calculate landslide hazard on cut slopes along the transportation lines. In data scarce natural slopes two methods will be used to estimate hazard: (i) using a rainfall threshold-based (temporal) probability model combined with a multivariate statistical analysis, and (ii) an inventory-based model by establishing a relationship between the number of landslides on cut slopes and natural slopes in different return periods.

5.1 Introduction

Landslide hazard is defined as the probability of occurrence of a potentially damaging landslide within a specified period of time and within a given area (Varnes, 1984). This definition incorporates the concepts of landslide magnitude (a measure of damaging or destructive power of a landslide), geographical location (ability to identify the place where a landslide can occur) and time of failure (Guzzetti et al., 1999; Crozier and Glade, 2005). Landslide hazard analysis is often carried out to estimate risk to life and property or to facilitate future land use planning. In literature different methods have been used to quantify hazard depending on the quality of landslide inventory, the type of landslides, the scale of the study and the aim of the analysis (e.g., Zezere et al., 2004; Chung and Fabbri, 2005; Guzzetti et al., 2005; Remondo et al., 2005; Catani et al., 2005; Harp et al., 2009).

Along the road and the railroad, landslides occur frequently from untreated cut slopes. Landslides initiating from cut slopes are generally small in size but pose considerable risk to life and property, as they may directly affect vehicles and persons below. To quantify risk along a road or a railroad, we require the estimation of the frequency of landslides (i.e., number of landslides per annum) and the degree of loss to specific elements at risk resulting from the specified landslide magnitude (AGS, 2000; Fell et al., 2005, 2008; van Westen et al., 2006). Researchers have used different statistical models to estimate frequency of landslides, such as those based on the probability density function of landslide volumes (e.g., Hungr et al., 1999), exceedance probability of a rainfall threshold (Jaiswal and van Westen, 2009) and the exceedance probability of landslides based on Poisson or Binomial probability models (e.g., Coe et al., 2000; Guzzetti et al., 2002,
Hazard analysis

(2005). The models based on rainfall threshold provide an estimate of the exceedance probability of one or more rainfall events that can trigger landslides, whereas those based on the occurrence of past landslides provide exceedance probability of one or more landslides that can occur in an area. Both threshold and landslide based-models are ultimately used to obtain the probability of occurrence of one or more landslides in a specified time period. For transportation lines, specific information on the expected number of landslides and their annual probability of occurrence (or return period) are important for estimating direct and indirect risk, expressed in terms of annualised loss. This information is used to estimate the probability of a landslide hitting a moving vehicle or a commuter (AGS, 2000; Wilson et al., 2005) and to calculate the blockage time by estimating the total volume of debris on the transportation line.

An estimate of the frequency of a specific number of landslides per unit area can be made if a relationship can be established between the number of landslides triggered by an event and the probability of occurrence of this event. To establish such a statistical relationship, we require a continuous record of landslide inventory. Some technical offices, such as road and railroad maintenance departments, or geotechnical offices, produce inventories containing continuous records of landslide occurrences within a region or along transportation lines. In this case the presence of a fairly complete landslide inventory for landslides on cut slopes allowed to estimate the probability of occurrence of landslides of a given size along different sections of the transportation lines. This can be done by analyzing the total number of landslides for different return periods, and multiplying this by the probability that the landslides belong to a given magnitude class. The result will give an estimate of certain number of landslides of a given magnitude class per section (e.g., per kilometer) of cut slopes for different return periods. This estimate is in accordance with the hazard descriptor for a transportation line recommended by Joint Technical Committee on landslides and Engineered Slopes, JTC-1 guidelines (Fell et al., 2008). The recommended descriptor expresses hazard as the number of landslides of a given magnitude (area or volume) per annum per kilometer of cut slopes.

Whereas the landslide hazard assessment along the transportation lines could be based on historical landslide information, and frequency analysis, another approach should be followed for the natural slopes, due to the lack of a complete landslide inventory.

In literature different approaches for landslide hazard analysis at a catchment scale are available (e.g., Glade, 2001; Guzzetti et al., 2005; Chung and
Fabbri, 2005). For landslides on natural slopes, the JTC-1 guidelines recommended using hazard descriptor as the annual probability of active landsliding for individual landslides and the number of landslides per unit area for small landslides on natural slopes. The JTC-1 guidelines also recommend carrying out hazard assessment according to the landslide type and magnitude.

In probabilistic terms, Guzzetti et al. (2005) included landslide area, which is considered a proxy for landslide magnitude, in the hazard assessment and calculated hazard as the joint probability of landslide size (area), of landslide occurrence in an established time period and of landslide spatial occurrence given the local environmental setting. The probabilistic model fulfills the definition of landslide hazard given by Varnes (1984), amended by Guzzetti et al. (1999) to include the magnitude of the landslide. Although one could argue this expression of landslide hazard as it assumes that the spatial probability, temporal probability and size probability are independent, it is currently the best applicable method for landslide hazard assessment at a medium scale (1:10,000 – 1:50,000). Other probabilistic methods that are based on process-based modeling, experience serious problems with parameterization, which makes their application problematic over larger areas (Kuriakose et al., 2009a).

One way to overcome the multiplication of the spatial, temporal and size probabilities by assuming independence and provide a combined probability would be to carry out a statistical analysis using a substantially complete event-based landslide inventory, an inventory of landslides caused by the same triggering event, and use the return period of the trigger as the temporal probability (e.g., Glade, 2001). In this method spatial probability of landslides for a given time is estimated as the ratio of landslide area to the susceptible area. As a limitation, complete event-based landslide inventories are difficult to obtain either through traditional photo-interpretation techniques, with the common problem of linking them to particular dates of occurrence (van Westen et al., 2006) or from historical landslide records, which often report only those landslides that have caused damage (Guzzetti et al., 1994; Chau et al., 2004; Devoli et al., 2007). In fact gap in historical records makes assessment of hazard probability very difficult.

In case of the unavailability of complete event-based landslide inventory, one way to estimate hazard is to make an assumption on the occurrences of future events, which include the number and sizes of future landslides expected in a given time (Chung and Fabbri, 2005). Hazard is then estimated as the ratio of landslide area to the map (susceptible) area. For this case
Hazard analysis

study, the inventory on cut slopes can be used to obtain information on the number and sizes of future landslides on natural slopes in different return periods by establishing a relationship between landslides affecting cut slopes and natural slopes in the area. The reliability of such information, however, depends on the completeness of the inventory on cut slopes.

For hazard analysis, the basic requirement is to obtain information on landslide susceptibility. This can be estimated using a variety of statistical techniques. Some of the commonly used techniques include logistic regression analysis (e.g., Atkinson and Massari, 1998; Ohlmacher and Davis, 2003; Suzen and Doyuran, 2004; Nefeslioglu et al., 2008), discriminant analysis (e.g., Baeza and Corominas, 2001; Carrara et al., 2003; Guzzetti et al., 2005), conditional analysis (e.g., Clerici et al., 2002), and weight of evidence (e.g., van Westen et al., 2003; Neuhaeuser and Terhorst, 2007). The above statistical techniques are usually based on two assumptions: first, that areas which have experienced landslides in the past are likely to experience them in the future and secondly, that areas with a similar set of geo-environmental conditions as that of the failed areas are also likely to fail in the future (Guzzetti et al., 1999; Fell et al., 2008). This means that the quantitative estimates of the spatial location of future landslide sources depend on the detailed information on the distribution of past landslides and a set of thematic variables such as slope angle, aspect, lithology, etc. that has initiated these landslides. The second assumption facilitates in predicting the geographical location of future landslides in passive areas (i.e., areas presently devoid of landslides) provided the geo-environmental conditions remain the same. The above assumptions have been successfully used for statistically quantifying landslide susceptibility. Problem occurs to add the temporal dimension to susceptibility maps at the catchment scale for the hazard analysis. Recently numerous publications have been made on methods to estimate temporal probability (e.g., Lee and Jones, 2004; Picarelli et al., 2005; Corominas and Moya, 2008).

The temporal probability of landslides can be estimated from past landslide records using various probability models assuming that the rate of occurrence of landslides would remain the same (e.g., Lips and Wieczorek, 1990; Coe et al., 2000; Guzzetti et al., 2002, 2005). The model provides the probability of getting one or more landslides at any given time. The statistics involved are simple and results are easy to implement, but the main limitation is that it requires a sufficiently complete landslide inventory of multiple periods to compute probability. Some researchers have used the frequency of occurrence of landslide triggers to estimate the temporal probability of landslides (e.g., Crozier, 1999; Chleborad et al., 2006). The advantage of
this method is that it does not require a complete multi-temporal landslide inventory but, it is necessary here to establish reliable relations between the trigger, its magnitude and the occurrence of landslides. This method can particularly help to model the temporal probability of first-time slope failures by determining the magnitude of trigger that has resulted in a slope to fail for the first time. Since the frequency of the trigger itself does not provide information on the spatial distribution of potential landslides, therefore it has to be combined with landslide susceptibility to produce a landslide hazard map (Corominas and Moya, 2008).

Another important consideration in the landslide hazard assessment is inclusion of landslide run-out distance in the hazard or susceptibility map. If an area has a potential for hazardous debris flows then the estimation of run-out distance is essential in order to evaluate the actual risk. Several empirical methods such as the mass-change method (Cannon and Savage, 1988), the angle of reach method (Hungr et al., 2005) and process based methods (Remaitre et al., 2005) are suggested for run-out calculation. The question remains, however, how to incorporate these for the many possible landslide initiation areas in a quantitative susceptibility map with many mapping units having different spatial probabilities (van Westen et al., 2006).

The run-out distance of a landslide depends on several factors, including the location of the landslide source with respect to the stream below, the volume of the landslide, the type of landslide, the saturation condition of debris and rheological behaviour, and the characteristics of the path such as slope angle, roughness, terrain geometry and land use (Dai et al., 2002). Ideally, all factors should be considered for the assessment of landslide run-out distance, but for a catchment area covering tens of square kilometers it is very difficult to obtain the required data on each of the factors. Therefore, in most cases run-out distance is empirically derived from the known landslides such as those based on the relationship of landslide height and length, volume and travel distance, etc.

5.2 Landslide hazard for cut slopes

5.2.1 Methodology

Figure 5.1 shows the work flow of the approach used to estimate landslide hazard along the road and railroad. For the hazard calculation, it is assumed that the probability of landslide occurrence can be calculated directly from the complete landslide inventory by analyzing the number of expected landslides per kilometer of the (rail) road for different return periods. For this the Gumbel method for frequency-magnitude analysis in which the
Hazard analysis

magnitude is represented as the number of landslides per kilometer is used. The volume of expected landslides was analyzed separately using the volume-frequency analysis. Given the limitations in the available data, it is assumed that the volume estimation is independent of the number of landslides triggered by the event.

The hazard, expressed as the probability of a given number of landslides with a particular volume to occur along a specific section of the road or railroad, was obtained by multiplying the probability of having a certain number of landslides per unit length resulting from the Gumbel analysis, with the results of the volume-frequency analysis.

Figure 5.1 Flow diagram for the quantitative assessment of landslide hazard along the road and railroad.
5.2.1.1 Estimation of landslide frequency and return period

The number of landslides varies significantly in different sections of the railroad and the road. For example, during the period from 1987 to 2007, a total of 785 landslides have occurred along the railroad of which the lowest number was recorded at km-26 (14 landslides) and the highest at km-12 (101 landslides). The number of landslides per kilometer per year varies from 1 to 25 along the railroad. The maximum number of landslides in a year was recorded in 2006 (25 landslides at km-11). The inventory suggests that a frequency of landslides of less than three landslides per year per kilometer is common in many sections, but extreme events (e.g., > 10 landslides per year per kilometer) occur less frequently. Thus it is possible to use the number of landslides per kilometer per year as an indication of the magnitude of the triggering events and calculate the frequency of occurrence based on the complete landslide inventory.

It is possible to relate the magnitude of extreme events to their frequency of occurrence through the use of probability distributions, such as the Gumbel extreme value distribution (Gumbel, 1958). The Gumbel function is frequently used in hydrological applications to model extreme events. In landslide studies, it was used to model return periods of landslide events through the analysis of precipitation and ground water changes (e.g., Miller, 1988; Odorico and Fagherazzi, 2003; Frattini et al., 2009). In a study focusing on the hazard along linear infrastructures such as roads or railroads the information on the expected number of landslides that can occur per unit length in a year and their probability of occurrence are essential for estimating the risk along the (rail) road. Furthermore, traffic disruption time and expected indirect loss can be modelled if information on the number of landslides per unit length is available. The cumulative probability distribution of the Gumbel extreme model can be applied in a landslide study to model the probability of occurrence of the number of landslides \( N_L \) equal to or less than some value \( n \). The model can be expressed as:

\[
P(N_L \leq n) = e^{-e^{(\alpha n)/c}}
\]

where \( \alpha \) and \( c \) are two parameters of the Gumbel distribution. By the method of moments, the parameters are evaluated as (e.g., Chow et al., 1988):

\[
\alpha = \gamma \sigma - \mu
\]

\[
c = \frac{\sqrt{6} \sigma}{\pi}
\]

83
where $\gamma = 0.57721$ is a Euler’s constant, $\mu$ is the mean, and $\sigma$ is the standard deviation. For a specified time interval in a year, Eq. (5.1) can be rewritten for the value $(N_L)$ equal to or greater than some value $n$ as:

$$P(N_L \geq n) = \frac{1}{T} = 1 - e^{-\frac{(\mu+n)}{\sigma}}$$

(5.4)

Two methods are commonly used for fitting distributions to the Gumbel model and using them for frequency analysis: the plotting position method and the frequency factor method. The former is a straightforward plotting technique to obtain the distribution function by use of certain ‘plotting position’ formulas (Chow et al., 1988). The technique is to arrange the data in increasing or decreasing order of magnitude and to assign order number $R$ to the ranked values. The Weibull formula is commonly used to obtain the plotting position, which for $P(N_L \geq n)$ can be expressed as:

$$P = \frac{R}{m+1}$$

(5.5)

where $R$ is the rank and $m$ is the total number of observations. When $R$ is ranked from lowest to highest, $P$ is an estimate of $P(N_L \leq n)$; when the rank is from highest to lowest, $P$ is $P(N_L \geq n)$. Eq. (5.5) can be plotted on a probability paper to represent the cumulative probability distribution. The graph is designed in such a way that it directly gives the return period and the corresponding magnitude of an event. The probability paper tends to linearize the distribution so that the plotted data can be easily analyzed for extrapolation or comparison purposes. When using the graphical method, it is recommended not to extrapolate the data more than two times the period of record; otherwise, the uncertainty in prediction will be high (Viessman et al., 1989).

To obtain the return period of a certain number of landslides per unit length (kilometer) along the transportation lines exceeding a given value, the yearly total number of landslides from cut slopes was selected for each kilometer section for the period 1987 to 2007. The total number of observations ($m$) is 21 years. The values were ranked from low to high. Using the plotting position method, the data were plotted on a probability paper and a curve was fitted to the plotted points.

An example of the result of the Gumbel plot for km-14 of the railroad is shown in Figure 5.2. In km-14, the maximum number of landslides triggered in a year was recorded in 2001 (11) and years without landslides were 1988, 1995 and 1997. The fitted straight line in the figure can be extrapolated to
make an estimate of the number of landslides in different return periods. As an example, for km-14 the figure gives nine landslides for a 15-year return period and 12 landslides for a 50-year return period.

**Figure 5.2** Gumbel plot for km-14 of the railroad. The plot is used to establish a relationship between the total number of landslides in this stretch of one kilometer and the return period.

Along the railroad, the Gumbel analysis was carried out for each of the 17 kilometer sections producing 17 Gumbel plots. Along the road, data on the occurrence of landslides were not available for every kilometer, and therefore, the Gumbel analysis was performed on two larger sections: a section with a length of 10 km (S-I, from km-390 to km-400) and a section of 14 km length (S-II, from km-400 to km-414). The two sections were selected on the basis of the difference in geomorphological setting and the density of landslide scars, which is the percentage of length of the road covered by landslide scars. In section S-I, the average density is 14 km\(^{-1}\), which is about three times higher than in section S-II. The average landslide density for the entire road is about 9 km\(^{-1}\). For each section of the railroad and the road, the expected number of landslides with \(T_1\), \(T_3\), \(T_5\), \(T_{15}\), \(T_{25}\) and \(T_{50}\) year return periods was estimated.
5.2.1.2 Estimation of landslide size probability

Along the railroad and road, the size of individual landslide is smaller than 6,000 m³, which is less than the upper boundary limit of the magnitude class M-III (M-III ranges between $10^3$ to $10^4$ m³). Therefore, to estimate the probability, three magnitude classes were used (M-I, M-II and M-III) as proposed in Section 4.2, Chapter 4. The probability value of magnitude class I, II and III was taken depending on the total number of landslides expected along the transportation lines in the given return period (Table 4.5). Since both transportation lines are located closely and both are affected by the same rainfall events, the total number of landslides expected along the railroad and the road were added for each return period to select the appropriate probability value.

5.2.2 Results

5.2.2.1 Landslide frequency and return period

Figure 5.3 shows results of the Gumbel analysis for each kilometer length along the railroad represented as smooth line graph. Results for the two sections along the road are given in Table 5.1. Results indicate that no landslide is expected to occur along the railroad and the road on average once every year, and one or more landslides can occur on an average once in three or more years. A four kilometer stretch of the railroad (from km-10 to km-13) is relatively more prone to landslides, as is the S-I section (from km-390 to km-400) along the road. Total 56, 84, 140, 164 and 197 landslides are expected to occur along the entire railroad, and about 14, 28, 55, 66 and 82 landslides are expected along the entire road in T3, T5, T15, T25 and T50 year return period, respectively.

The results indicate that the maximum number of landslides per kilometer is expected towards the east of Burliyar. This section of the transportation lines also has the maximum probability of experiencing rainfall events that can trigger one or more landslides (Figure 4.6).

<table>
<thead>
<tr>
<th>Road section</th>
<th>Number of landslides per kilometer</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>T3</td>
</tr>
<tr>
<td>S-I (total length 10 km)</td>
<td>0</td>
</tr>
<tr>
<td>S-II (total length 14 km)</td>
<td>0</td>
</tr>
</tbody>
</table>
5.2.2.2 Probability of landslide volume

The results show that in total 70, 112, 195, 230 and 279 landslides are expected to occur along both the road and railroad in T3, T5, T15, T25 and T50 year return period, respectively. More than 100 landslides are expected on average once in five or more years and therefore the probability of landslide magnitude for T5, T15, T25 and T50 is taken as 0.39 for M-I, 0.53 for M-II and 0.08 for M-III, as given in Table 4.5. For T3 return period, with less than 100 landslides, the probability is taken as 0.85 for M-I, 0.13 for M-II and 0.02 for M-III (Table 4.5).

5.2.2.3 Landslide hazard

In total, 18 specific hazard scenarios were generated using combinations of the three volume classes (M-I, M-II and M-III) and six return periods (T1, T3, T5, T15, T25 and T50 year). An example of three hazard scenarios for T50 year return period are given in Table 5.2 (for the railroad) and Table 5.3 (for the road). The hazard categories H-I, H-II and H-III show the number of landslides of magnitude class M-I, M-II and M-III, respectively that occur per kilometer of cut slopes in a 50-year return period. The analyses show that on average once in 50 years (annual probability of 0.02), the entire railroad will be affected by 77, 104 and 16 landslides, and the road by 32, 43 and 7 landslides of H-I, H-II and H-III hazard, respectively.
### Table 5.2 Landslide hazard along the railroad in T50 year return period.

<table>
<thead>
<tr>
<th>Kilometer mark along the railroad</th>
<th>Number of landslides per kilometer</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>H-I</td>
</tr>
<tr>
<td>Km-10</td>
<td>8.2</td>
</tr>
<tr>
<td>Km-11</td>
<td>10.1</td>
</tr>
<tr>
<td>Km-12</td>
<td>8.9</td>
</tr>
<tr>
<td>Km-13</td>
<td>7.1</td>
</tr>
<tr>
<td>Km-14</td>
<td>4.7</td>
</tr>
<tr>
<td>Km-15</td>
<td>4.8</td>
</tr>
<tr>
<td>Km-16</td>
<td>4.1</td>
</tr>
<tr>
<td>Km-17</td>
<td>3.8</td>
</tr>
<tr>
<td>Km-18</td>
<td>3.3</td>
</tr>
<tr>
<td>Km-19</td>
<td>2.7</td>
</tr>
<tr>
<td>Km-20</td>
<td>2.6</td>
</tr>
<tr>
<td>Km-21</td>
<td>2.8</td>
</tr>
<tr>
<td>Km-22</td>
<td>3.4</td>
</tr>
<tr>
<td>Km-23</td>
<td>2.7</td>
</tr>
<tr>
<td>Km-24</td>
<td>2.8</td>
</tr>
<tr>
<td>Km-25</td>
<td>2.5</td>
</tr>
<tr>
<td>Km-26</td>
<td>2.2</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>76.7</td>
</tr>
</tbody>
</table>

H-I, H-II and H-III are the hazard related to landslide of M-I, M-II and M-III, respectively.

### Table 5.3 Landslide hazard along the road in T50 year return period.

<table>
<thead>
<tr>
<th>Road section</th>
<th>Number of landslides per kilometer</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>H-I</td>
</tr>
<tr>
<td>S-I (total length 10 km)</td>
<td>2.39</td>
</tr>
<tr>
<td>S-II (total length 14 km)</td>
<td>0.58</td>
</tr>
</tbody>
</table>

H-I, H-II and H-III are the hazard related to landslide of M-I, M-II and M-III, respectively.

### 5.3 Landslide hazard for natural terrain

Two different approaches are presented for estimating landslide hazard for natural terrain above and below the transportation lines. The availability of information on the date of landslides and daily rainfall provided the opportunity to propose a probabilistic model based on a rainfall threshold to quantify hazard. The second approach is based on the statistical analysis of landslides on cut slopes to assess landslide hazard for natural slopes in different return periods. The method uses a relationship between cut slope and natural slope failures to estimate the number and sizes of landslides expected on natural slopes.
5.3.1 Threshold-based method for hazard analysis

Figure 5.4 shows the work flow of the rainfall threshold-based approach for landslide hazard estimation. It requires the estimation of three basic parameters:

1. the magnitude probability \( (P_M) \): indicating the probability that the landslide might be of a given size,
2. the temporal probability \( (P_T) \): indicating the annual probability of occurrence of triggering events that generate landslides, and
3. the spatial probability \( (P_S) \): indicating the relative spatial probability of occurrence of landslides of a given type.

Using the above probabilities, the landslide hazard on natural slopes can be estimated as the joint probability of the landslide size (volume), of the landslide occurrence in an established time period using rainfall threshold related to first-time slope failures and of the landslide spatial occurrence given the local environmental setting, based on the method adapted from the earlier work presented by Guzzetti et al. (2005). It is assumed that the above three probabilities are mutually independent and the landslide hazard \( (H_L) \), i.e., the joint probability is:

\[
H_L = P_M \times P_T \times P_S
\]  

The assumption that the three probabilities in Eq. (5.6) are mutually independent may not hold always and everywhere. Small triggering events will result in another landslide magnitude distribution than a large triggering event, and also the locations where landslides will occur may be substantially different. However, the assumption is accepted here as the best approach given the lack of a better approach that can be used under the given circumstances of data availability and characteristics of the study area.

5.3.1.1 Assessment of magnitude probability of landslides

The method used to estimate the probability of landslide volume for landslides on natural slopes is discussed in Section 4.3.4. Figure 4.12 shows the probability that a landslide exceeds a volume of 1,000 m\(^3\) (0.07) and a volume of 10,000 m\(^3\) (0.01). These values were used in the estimation of landslide hazard. The obtained model is validated using landslide events of 2009 (see Section 7.3, Chapter 7).
5.3.1.2 Assessment of temporal probabilities of landslides

The temporal probability was estimated indirectly using the exceedance probability of a rainfall threshold required to trigger landslides on natural slopes. The availability of a multi-temporal landslide inventory (Table 3.2) and rainfall records allowed establishing threshold values for landslides on
natural slopes. The event inventories indicate that out of 111 recorded landslide events only seven have triggered landslides on natural slopes, of which five occurred during the period between 1992 and 2006. These events were used to manually draw an envelope curve following the method discussed in Section 4.1.3.1. For the threshold analysis, 5-days antecedent rainfall ($R_{5ad}$) as deduced for threshold pertaining to the entire railway route was used. The threshold line is represented by a linear mathematical equation given by $R_T = 210 - 0.54 R_{5ad}$. The small slope (0.54) and high intercept (210) of the envelope curve indicates that such events either require very high magnitude daily rainfall or a very high amount of a five-day antecedent rainfall during the monsoon to trigger landslides.

In chapter 4, it was shown that there are about 12 events that have triggered more than 15 landslides along the railroad during October to December. The 12 events are represented by a threshold equation ($R_T = 220 - 0.61 R_{5ad}$) which is similar to the threshold established for landslides on natural slopes. Due to the similarity in the equations it can be inferred that in the historical records landslides were not reported on natural slopes for at least seven occasions when rainfall was very high and triggered more than 15 landslides along the railroad. This information can be used to infer the frequency of occurrence of landslides after the threshold has been exceeded.

The temporal probability of threshold exceedance over a specified time period, which also gives the probability of landslide initiation on natural slopes, is estimated in four sections shown in Figure 4.1. The method adopted for calculating frequency of rainfall ($R$) exceeding the threshold value ($R_T$) in the four sections is the same as described in Section 4.1.4. For each section, based on the past rate of $R > R_T$, threshold recurrence was obtained i.e., the expected time between successive threshold exceedances. Knowing the mean recurrence interval of threshold in each section (from 1992 to 2006), and adopting a Poisson probability model (Eq. (4.4)), the probability of the threshold being exceeded $P(R > R_T)$ in specified years in each section was computed. Due to the possible incompleteness of the landslide data, the value of $P[L|R > R_T]$ in Eq. (4.3) is taken as 0.73, which is the same as estimated for the entire railway route with a similar threshold equation. Since events triggering landslides on natural slopes require very high daily and antecedent rainfall, it is assumed that under the given high rainfall condition the likelihood of triggering landslides is also high, such as those estimated for the entire railway route $P[L|R > R_T] = 0.73$.
5.3.1.3 Assessment of landslide susceptibility

Selection and classification of preparatory factors

For susceptibility mapping, the selection of preparatory factors for landslides depends on the scale of analysis, the characteristics of the study area, the landslide type, the failure mechanisms and the priori knowledge of the main causes of landslides (Guzzetti et al., 1999; Glade and Crozier, 2005). A systematic overview of the important preparatory factors required for susceptibility mapping in different scales is given in van Westen et al. (2008). A priori knowledge of the main causes of landslides in the area of interest is essential in selecting the most relevant factors out of the many known preparatory factors that can “theoretically” cause landslides (Ghosh and Carranza, 2010).

In the study area, landslides on natural slopes are individually small in size and affect only the overburden soils and regolith. From the field observation it appears that the terrain characteristics, land use and thickness of regolith are the key factors controlling mass movements in the area. The earlier report on the landslide susceptibility also indicated slope angle, changes in the land use and thickness of regolith as the main causal factors for the initiation of debris slides and debris flowslides in the Nilgiri hills (Seshagiri and Badrinarayanan, 1982). The report did not include lithology and structure as preparatory factors because these have no direct influence in causing landslides except in the development of overburden soils. In the earlier report some of the key factors related to the terrain morphometry such as flow accumulation, topographic wetness, internal relief, etc were not considered because these were difficult to generate manually. However, with GIS based analysis it is now possible to generate different types of terrain morphometric maps and to indirectly model surface hydrology which could help in the better analysis of rainfall-induced landslides.

Based on the field evidences and the facts given in the earlier report (Seshagiri and Badrinarayanan, 1982), nine factor maps were prepared that are considered to be the main spatial causal factors for landslides in the area. Out of the nine maps, six are related to terrain morphometry derived from DTM, two are field based maps and one related to distance. A brief description of the significance and mapping techniques for each factor is given below.

1) Slope angle – the slope angle was derived from a digitized topographic map with 10 m contour spacing that was interpolated in a 10 m regular grid DTM using Arc GIS 9.3 (Figure 5.5A). The slope map was reclassified into 13 classes with intervals of $5^\circ$. Slope angle varies between $0^\circ$ and
76°. In general landslide frequency increases with the slope gradient until the maximum frequency is reached in the 35–40° categories, followed by a decrease (Lee and Min, 2001; Dai and Lee, 2002). In this case, the landslide distribution indicates that landslide frequency increases with the slope angle until the maximum is reached in the 25°–30° categories, followed by a decrease. The areas with more vertical slopes with outcropping bedrock were found to be stable and not susceptible to landslides. During the 1978 and 1979 landslide events, 69% of debris slides occurred within slope angles ranging from 10° to 35°. They occurred on steep slopes (> 25°) in 1978 and relatively gentler slopes (~10°) in 1979.

2) Aspect - the aspect (direction) of a slope may also contribute to landsliding. The moisture retention and vegetation are generally reflected by the slope aspect, which may affect soil strength and susceptibility to landslides. The slope aspect was also derived from the DTM using Arc GIS 9.3 (Figure 5.5B) and the values were grouped into 12 classes with intervals of 30°.

3) Internal relief – The internal relief represents the height difference per unit area. This map (Figure 5.5C) was created in ILWIS 3.7 by first obtaining the minimum and maximum elevation per hectare using a ‘moving filter’ after which the height difference was calculated for each pixel. In the high relief areas (steeper topography) the surface run-off is higher and the infiltration is lower and thus expected to have more erosion.

4) Slope shape (profile curvature) - Slope shape was also derived in a 10 m regular grid DTM using Arc GIS 9.3 (Figure 5.5D). A positive curvature represents upwardly convex surface, while a negative curvature indicates that the surface is upwardly concave at a given pixel. The concave hill slopes are areas having high soil moisture content and receive more surface run-off. Failures can be expected to occur more frequently in those areas than the slopes that are convex along the contour.

5) Flow accumulation – the flow accumulation is a measure of the area that contributes surface run-off to an area where material can accumulate. In the case of surface water run-off flow accumulation defines the location of water concentration after rainfall and those locations are likely to have a high landslide incidence (Dahal et al., 2008). It is DTM-based derivative and the DEM hydro-processing operation in ILWIS 3.7 calculates flow accumulation of a watershed (Figure 5.5E).
Hazard analysis

6) Topographic wetness index – The topographic wetness index (TWI) is a derivative of flow accumulation and is taken as a parameter that relates the local soil moisture status (Figure 5.5F). It describes the effect of topography on the location and size of saturated source areas of run-off generation. Since modelling of water in soil slopes at a catchment scale is difficult because of the variability in the factors that governs soil water content, therefore TWI is taken as a representative of the topographic control on soil wetness, which is an indirect indicator for soil water content.

7) Land use – The land use map was prepared from the 1998 surveyed 1:25,000 scale topomap and Cartosat-1 stereo data (2.5 m resolution) of April 2007 (Figure 5.5G). Most of the steeper slopes are under forest and gentler slopes are used for tea plantation. In the past 100 years few changes in land use have taken place in the area near Katteri where several new buildings have been constructed. The total area of the reserved forest and the tea estates has not been changed over time.

8) Regolith thickness – In shallow landslides, where the slip plane is the contact zone of rock and regolith, a thin regolith cover increases the chance of landsliding due to the build-up of pore pressure on the contact (Iverson, 2000; Zezere et al., 2005). In the study area, the variation in the thickness of regolith was observed to be very erratic. On the hill slopes the thickness was found to vary significantly except near the Katteri area. The thickness depends on a large variety of factors, one important being the local variation in terrain morphology and therefore prediction of the regolith thickness over a large area is extremely difficult. Ideally for thickness modelling a large number of observations (such as drill holes, outcrops, or geophysical measurements) are required. However, at a catchment scale this approach is difficult to implement. Given the above mentioned limitations and difficulties, a point interpolation technique based on the inverse distance weighing method was used to obtain a regolith thickness map for the study area. In a small catchment area of the Western Ghat of southern India interpolation methods have been used successfully for predicting soil depth (Kuriakose et al., 2009b). For interpolation, the points were measured at 246 locations in the field as the thickness of regolith cover exposed along the road, railroad, streams and landslide scars. The selected point locations were distributed in most part of the study area, except towards the north where the slopes are very gentle and covered by tea plantations. Using the geo-statistical software 'R', the measured points were then used to build up an empirical variogram, which was subjected to automatic fitting using a spherical model. The resulting partial sill was 14.2 and nugget of
13.1 with the maximum range of 573.3. These values were used in the interpolation at 10 m resolution and a regolith thickness map was generated for the entire corridor area (Figure 5.5H). The prediction of regolith thickness was better around areas where data were taken and the accuracy was lower in areas located away from the sample points. Since the density of sample points was high and closely located in areas that are susceptible to landslides the prediction of the regolith thickness was relatively better in these areas.

9) Distance from drainage – along the drainage most landslides occur due to the slope undercutting during a high discharge condition and its effect decreases with the increase in the distance from the drainage. Using the distance calculation function of ILWIS 3.7 a continuous distance map was initially prepared for all drainages and later reclassified into different buffer zones as shown in Figure 5.5I.

Besides the factor maps mentioned, distance from roads and railroad is also an important factor if the landslides are related to cut slopes. The present susceptibility analysis considers only landslides on natural slopes (Figure 5.6) and therefore this factor is not considered here. All the nine maps shown above are 'theoretically' key preparatory factors for rainfall-induced debris slides, but for the susceptibility analysis it is necessary to select only those factors that bear a clear relationship with mass movement in the study area otherwise the statistical analysis may produce results that are unreliable (Guzzetti et al., 1999; Ghosh et al., 2009). In order to quantify the spatial association of different factor maps with the known landslide occurrences, two different methods were used: (1) distance distribution method for a continuous variable and (2) weights of evidence method for a categorical variable.

The distance distribution method is used to quantify the spatial association between a set of known point objects and another set of objects with a particular geometry. It has been widely used in mineral exploration (e.g., Bonham-carter et al., 1985; Carranza, 2009). In landslides, the method involves comparing a cumulative relative frequency distribution of distances from a set of factor classes to known landslide locations \( D_l \) and a cumulative relative frequency distribution of distances from the same set of factor classes to non-landslide locations \( D_{nl} \). If the difference \( D \) of the graphs \( D_l \) and \( D_{nl} \) is equal to 0, then the landslides and the set of factor classes are spatially independent. If \( D \) is positive (i.e., \( > 0 \)), which means that the graph of \( D_l \) plots above the graph of \( D_{nl} \), then there is a positive spatial association between the landslides and the set of factor classes. If \( D \) is
negative (i.e., < 0), which means that the graph of $D_L$ plots below the graph of $D_N$, then there is a negative spatial association between the landslides and the set of factor classes. A positive spatial association represents a plausible control of the set of factor classes on the distribution of the landslides (Ghosh and Carranza, 2010).

The known occurrences of landslides on natural slopes (Figure 5.6) have a positive spatial association with slope which is optimal at 26° (Figure 5.7A). 75% of all landslides are present on slopes above this value, and according to the curve for $D_l$, there is at most 15% higher occurrence of landslides than would be expected due to chance. Internal relief also shows positive spatial association and the positive spatial association is optimal at 27 index value (Figure 5.7B). Flow accumulation (Figure 5.7D), topographic wetness index (Figure 5.7E) and distance from drainage (Figure 5.7F) also have a positive spatial association with known landslides. Figure 5.7C shows that the known occurrences of landslides on natural slopes have a negative spatial association with slope shape, which is probably because a similar proportion of landslides might have affected both concave and convex slopes.

For a categorical variable, using weights of evidence method one can determine the favorability of locating a landslide given the presence or absence of a factor class. The method was originally developed for mineral potential mapping (Bonham-Carter, 1994) and later has been adapted in landslide susceptibility mapping by various researchers (e.g., van Westen et al., 2003; Neuhaeuser and Terhorst, 2007).

By overlaying landslide locations with each factor, the statistical relationship can be measured between them, and a pair of positive (W+) and negative (W-) weights is calculated for each factor. In terms of the spatial association between the factor and the landslide, the value of $W_+ > 0$ and $W_- < 0$ indicates positive spatial association, whereas $W_+ < 0$ and $W_- > 0$ indicates a negative spatial association, and $W_+ = W_- = 0$ reflects a lack of spatial association. To quantify the relative importance of a spatial association between a factor class and the occurrence of landslides, the contrast factor ($C_w$), as mentioned in Bonham-Carter (1994) is taken as a tool, which represents a positive spatial correlation if $C_w > 0$ and a negative spatial correlation if $C_w < 0$. The method is explained in more detail in Castellanos (2008).
Figure 5.5 Landslide preparatory factor maps: slope angle (A), aspect (B), internal relief (C), slope shape (D), flow accumulation (E), topographic wetness index (F), land use (G), regolith thickness (H) and distance from drainage (I).
Hazard analysis

Figure 5.6 Location of landslide source and run-out areas on natural slopes. Sections I, II, III and IV are the areas used for determining rainfall thresholds.

The variations in contrast $C_w$ for different factor classes of aspect, land use and regolith thickness with respect to the known occurrences of landslides are shown in Table 5.4. For aspect the contrasts are mostly negative or not significantly greater than zero, which indicate a dominant negative spatial association except for southerly ($121^\circ - 180^\circ$) facing slopes. Significant positive spatial association is indicated by forest, horticulture and scrubs. Similarly, regolith thickness is mostly negative correlated except of thickness 5 to 10 m which shows significant positive spatial association with landslides.

Based on the results of the spatial association test, eight factor maps were selected for the susceptibility analysis that showed positive spatial association with the known landslides. These maps were classified into 52 factor classes and used as independent variables: slope angle (13 classes), aspect (12 classes), land use (8 classes), regolith thickness (4 classes), topographic wetness index (3 classes), internal relief (5 classes), flow accumulation (4 classes) and distance from drainage (3 classes). The boundary limit of the factor classes of continuous variables was taken depending on the level of spatial association that each class had with the landslides as indicated by the difference ($D$) of the cumulative relative frequency distributions.

The dependent variable includes source areas of the existing landslides on natural slopes that occurred between 1987 and 2007 (Figure 5.6). Their source areas range from 60 to 15,000 m$^2$. 
Figure 5.7 Graphs of cumulative relative frequency of distances at known landslide locations ($D_L$) and non-landslide locations ($D_{NL}$) around factor classes.
Table 5.4 Variation of contrasts in different factor classes with respect to the known landslide occurrences.

<table>
<thead>
<tr>
<th>Factor class</th>
<th>$C_w$</th>
<th>Factor class</th>
<th>$C_w$</th>
<th>Factor class</th>
<th>$C_w$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aspect</td>
<td></td>
<td>Land use</td>
<td></td>
<td>Regolith thickness</td>
<td></td>
</tr>
<tr>
<td>00° - 30°</td>
<td>-1.78</td>
<td>Tea</td>
<td>-2.13</td>
<td>&lt; 1 m</td>
<td>-0.02</td>
</tr>
<tr>
<td>31° - 60°</td>
<td>-1.40</td>
<td>Forest</td>
<td>1.63</td>
<td>1 - 5 m</td>
<td>-0.43</td>
</tr>
<tr>
<td>61° - 90°</td>
<td>-3.08</td>
<td>Settlement</td>
<td>-1.21</td>
<td>5 - 10 m</td>
<td>0.76</td>
</tr>
<tr>
<td>91° - 120°</td>
<td>-2.21</td>
<td>Barren (rocky)</td>
<td>-0.02</td>
<td>&gt; 10 m</td>
<td>-0.77</td>
</tr>
<tr>
<td>121° - 150°</td>
<td>0.41</td>
<td>Coffee</td>
<td>-0.03</td>
<td></td>
<td></td>
</tr>
<tr>
<td>151° - 180°</td>
<td>0.97</td>
<td>Horticulture</td>
<td>0.24</td>
<td></td>
<td></td>
</tr>
<tr>
<td>181° - 210°</td>
<td>-0.22</td>
<td>Scrubs</td>
<td>1.52</td>
<td></td>
<td></td>
</tr>
<tr>
<td>211° - 240°</td>
<td>-0.36</td>
<td>Tea with trees</td>
<td>-0.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>241° - 270°</td>
<td>-2.57</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>271° - 300°</td>
<td>-0.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>301° - 330°</td>
<td>-0.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>331° - 359°</td>
<td>-0.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table entries in bold pertain to optimal spatial association.

Selection of mapping units and susceptibility modelling
After the selection of appropriate preparatory factors, the next step was the selection of mapping units for the GIS based susceptibility analysis.

Landslide processes are highly controlled by the slope features of the terrain, namely drainage and divide lines (Carrara et al., 1992) and therefore slope-units are best suited for a hazard analysis. But for selecting a mapping unit importance must be given to the type of landslides in the area, mapping scale and scope of the work. In this study, the area of individual landslide sources is small and slope-units covering relatively large areas often do not match with the local geo-environmental setting related to slope instability. One way to overcome this is to resize the slope-units according to the present landslide size by partitioning a river basin into nested subdivisions, coarser for larger landslides and finer for smaller failures (Guzzetti et al., 1999). But, for application purposes this approach is not suitable for small and shallow landslides (Montgomery and Dietrich, 1994). Furthermore, even with GIS it is still difficult to manually digitize irregular mapping units of a very small size e.g., the slope unit of area < 100 m². In this work, because of the small size of the landslide source area, pixels was selected as the basic mapping unit for the susceptibility modelling so that the smallest landslide can be represented by a single pixel. As an additional advantage, a pixel based mapping unit can facilitate very fast computation and processing of the raster data set in GIS and it is also the commonly used units in the raster based analysis (Carrara et al., 1992). The 22 km² study area was converted into an equal-area grid by rasterizing the polygon map using a 10 m × 10 m pixel size.
For the susceptibility analysis, a logistic regression (LR) model in 'R-software' was used for the classification of susceptibility. The model helps in establishing a multivariate relation between a dependent (landslide) and several independent variables, which are the preparatory factors for landslides. In the LR model, the dependent variable $z$ is dichotomous, which is a binary value and it is TRUE if a landslide is present and FALSE if it is absent, and independent variables are either categorical or continuous. The model aims to establish the probability that a mapping unit contains a landslide ($z = \text{TRUE}$) given the set of independent variables (Atkinson and Massari, 1998). The model can be written in its simplest form as:

$$
P = \frac{1}{1 + e^{-z}}$$  \hspace{1cm} (5.7)

where $P$ is the estimated probability of landslide occurrence. This probability can be modelled by regression equation, which is defined as:

$$
z = \beta_0 + \beta_1 B_1 + \beta_2 B_2 + \beta_3 B_3 + \ldots + \beta_n B_n$$  \hspace{1cm} (5.8)

where $\beta_0$ is the intercept of the model, $n$ is the number of independent variables, $\beta_i$ ($i=0,1,\ldots,n$) are the coefficients estimated from the sample data, and $B_i$ ($i=1,2,\ldots,n$) are the independent variables. When the value of $z$ varies from $-\infty$ to $+\infty$, the probability varies from 0 to 1 on an s-shaped curve. The coefficients in the LR model are estimated using the maximum-likelihood method or in other words, the coefficients that make the observed results most 'likely' are selected. In the R-software, the regression model is fitted using iteratively reweighted least squares method under the link function (link=logit). The model uses Akaike's information criterion (AIC) to know the 'goodness' of the model in response to added independent variables or to know whether the model has gained anything by adding a variable (Venables et al., 2007).

The logistic regression analysis is well known to have been designed to work on the dataset that are more or less equal in size (Garcia-Ruiz et al., 2003; Nefeslioglu et al., 2008) but there are many studies where the ratio of landslide presence (1)/landslide absence (0) is taken as unequal proportions (e.g., Atkinson and Massari, 1998; Guzzetti et al, 1999; Dai and Lee, 2002; Ohlmacher and Davis, 2003; Ayalew and Yamagishi, 2005). Studies have shown that where landslides are rare events i.e., if the mapping units with landslide presence are thousands of times fewer than their absence (King and Zeng, 2001), then taking unequal proportions of the ratio of landslide presence /absence the model tends to sharply under predict the probability of rare events (Garcia-Ruiz et al., 2003). Since, the susceptibility map produced
by a logistic regression technique is directly controlled by the ratio of presence/absence of landslides in the mapping units, any increase of mapping units free from landslides tends to decrease the areas susceptible to landslides in the susceptibility map. Contrary to this, the susceptible areas to landslides increase with a decrease in the ratio of absence/presence of landslides (Can et al., 2005). In this case study, the input dependent variable (landslide source area) can be considered as a rare event as it is represented by 646 pixels, which is thousands of times fewer than their absence.

Can et al. (2005) recommended the use of an equal proportion of landslide presence/landslide absence if the event is considered rare. His recommendation was based on the study performing a series of sensitivity analyses using randomly selected different ratios of the mapping units with the absence of landslides to the mapping units including landslides. Following the above recommendation, an equal number of pixels from the non-landslide areas was selected as samples representing the absence of landslide against the 646 pixels representing the presence of landslides. In this work only one training dataset was used because studies have shown that selecting different training sets, randomly chosen from the landslide free areas, do not have much effect on the performance of the model (Yesilnacar and Topal, 2005).

The preparatory factors (slope angle, aspect, land use, regolith thickness, topographic wetness index, internal relief, flow accumulation and distance from drainage) and landslide maps formed the input parameters for the susceptibility modelling. All factor maps were converted into an equal-area grid by rasterizing them using a 10 m×10 m pixel size. The model was subjected to iterative modelling and at the initiation all the 52 factor classes (independent variables) were used. One by one each factor was withdrawn from the model and the performance was judged based on AIC values. The model performed best when the topographic wetness index was withdrawn and showed the lowest estimated AIC value (1190).

Judgment of the performance of the training dataset was based on the Receiver Operating Characteristics (ROC) curve (Zweig and Campbell, 1993). The ROC curve is a plot of the sensitivity (proportion of true positives) of the model prediction against the complement of its specificity (proportion of false positives), at a series of thresholds for a positive outcome. Sensitivity is the probability that a mapping unit with landslide is correctly classified, and is plotted on the y-axis in an ROC curve; sensitivity is the false negative rate. Specificity is the probability that a mapping unit with no-landslide is correctly classified; 1 – specificity is the false positive rate and is taken along the x-
axis of the curve. The area under the curve represents the probability that the landslide susceptibility value for a landslide mapping unit calculated by the model will exceed the result for a randomly chosen non-landslide mapping unit. The ROC curve for the model developed is given in Figure 5.8 and the area under the curve obtained is 0.87, which gives an accuracy of 87% for the training model.

![Figure 5.8 Receiver operator characteristic curve.](image)

Table 5.5 shows the coefficients of different factor classes derived from the logistic regression model. The positive and negative coefficients respectively indicate the contribution of the variable towards increasing and reducing the likelihood of landslides in the mapping unit. As an example, almost all classes of slope and south facing slopes (aspect~121° - 210°), forest and scrubs favour the probability of the occurrence of landslides. To the contrary, NE and SW facing slopes in a mapping unit are in favour of its stability. The estimated coefficients from the model output were used to compute $z$ by using Eq. (5.8). The probability value was then estimated at each pixel by using Eq. (5.7).

The statistical method can classify the area into different susceptibility classes but the question remains how well the model has performed in classifying the area? The quantitative estimate of its performance was evaluated by using reliability tests, such as error matrix and success rate curve.

The error matrix is a straightforward way of testing a model fit by computing the percentage of cases (i.e., percentage of mapping units) correctly
Hazard analysis

classified by the susceptibility model. It requires a base map containing known cases having known stable and unstable slopes. The most commonly used cases are known landslides from the inventory (Guzzetti et al., 2006), and a mapping unit is considered stable if it is free of landslide and unstable if it contains a landslide. In logistic regression high and low values of membership probability indicate hazardous and safe mapping units, respectively. Values close to 0.5 is the most uncertain and do not provide any information with respect to the input landslide map (Guzzetti et al., 1999). Therefore in this analysis, for the susceptibility model, the mapping units are grouped as unstable if the units have a probability value > 0.6 and stable if the probability is ≤ 0.6.

Table 5.5 Coefficients derived from logistic regression model.

<table>
<thead>
<tr>
<th>Factor class</th>
<th>Class code</th>
<th>Coefficient</th>
<th>Factor class</th>
<th>Class code</th>
<th>Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td></td>
<td>-0.61</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slope</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>05º - 10º</td>
<td>SLOPEB</td>
<td>15.32</td>
<td>Coffee</td>
<td>LANDE</td>
<td>-17.47</td>
</tr>
<tr>
<td>10º - 15º</td>
<td>SLOPEC</td>
<td>16.65</td>
<td>Horticulture</td>
<td>LANDF</td>
<td>2.91</td>
</tr>
<tr>
<td>15º - 20º</td>
<td>SLOPED</td>
<td>17.52</td>
<td>Scrubs</td>
<td>LANDG</td>
<td>17.87</td>
</tr>
<tr>
<td>20º - 25º</td>
<td>SLOPEE</td>
<td>16.90</td>
<td>Tea with trees</td>
<td>LANDH</td>
<td>-16.99</td>
</tr>
<tr>
<td>25º - 30º</td>
<td>SLOPEF</td>
<td>17.35</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>30º - 35º</td>
<td>SLOPEG</td>
<td>17.67</td>
<td>Regolith thickness</td>
<td>REGTHB</td>
<td>-16.14</td>
</tr>
<tr>
<td>35º - 40º</td>
<td>SLOPEH</td>
<td>17.35</td>
<td>1 – 5 m</td>
<td>REGTHC</td>
<td>-15.99</td>
</tr>
<tr>
<td>40º - 45º</td>
<td>SLOPEI</td>
<td>15.75</td>
<td>5 – 10 m</td>
<td>REGTHD</td>
<td>-15.61</td>
</tr>
<tr>
<td>45º - 50º</td>
<td>SLOPEJ</td>
<td>16.25</td>
<td>&gt; 10 m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>50º - 55º</td>
<td>SLOPEK</td>
<td>16.02</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>55º - 60º</td>
<td>SLOPEL</td>
<td>16.19</td>
<td>Internal relief</td>
<td></td>
<td></td>
</tr>
<tr>
<td>&gt; 60º</td>
<td>SLOPEM</td>
<td>16.02</td>
<td>15 – 25 m</td>
<td>IRB</td>
<td>-1.18</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>25 – 35 m</td>
<td>IRC</td>
<td>-1.02</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>35 – 50 m</td>
<td>IRD</td>
<td>-0.05</td>
</tr>
<tr>
<td>Aspect</td>
<td></td>
<td></td>
<td>&gt; 50 m</td>
<td>IRE</td>
<td>2.81</td>
</tr>
<tr>
<td>31º - 60º</td>
<td>ASPB</td>
<td>-0.31</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>61º - 90º</td>
<td>ASPC</td>
<td>-2.77</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>91º - 120º</td>
<td>ASPD</td>
<td>-2.43</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>121º - 150º</td>
<td>ASPE</td>
<td>0.86</td>
<td>Flow accumulation (×100 m²)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>151º - 180º</td>
<td>ASPF</td>
<td>1.02</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>181º - 210º</td>
<td>ASPG</td>
<td>0.39</td>
<td>5 – 15</td>
<td>FLB</td>
<td>-0.02</td>
</tr>
<tr>
<td>211º - 240º</td>
<td>ASPH</td>
<td>-0.31</td>
<td>15 – 25</td>
<td>FLC</td>
<td>0.82</td>
</tr>
<tr>
<td>241º - 270º</td>
<td>ASPI</td>
<td>-2.06</td>
<td>&gt; 25</td>
<td>FLD</td>
<td>0.63</td>
</tr>
<tr>
<td>271º - 300º</td>
<td>ASPJ</td>
<td>-17.40</td>
<td>Distance from drainage</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Land use</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Forest</td>
<td>LANDB</td>
<td>0.16</td>
<td>25 – 50 m</td>
<td>DDB</td>
<td>-0.33</td>
</tr>
<tr>
<td>Settlement</td>
<td>LANDC</td>
<td>-0.14</td>
<td>&gt; 50 m</td>
<td>DDC</td>
<td>-1.98</td>
</tr>
<tr>
<td>Barren (rocky)</td>
<td>LANDD</td>
<td>-32.51</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

AIC = 1190

The error matrix provides the estimate for model fit or “overall goodness of fit” but does not provide a detailed description of the model performance of the different susceptibility classes. The model performance was judged using
a success rate curve proposed by Chung and Fabbri (1999). The success rate curve was obtained using landslides that were previously used in building the model. It was calculated by ordering the pixels of a susceptibility map in a number of classes, from high to low values. The success rate indicates how much percentage of all landslides occurs in the classes with the highest susceptibility values. It measures the effectiveness of the model and is a useful indicator for the quality of the map (van Westen et al., 2003).

Although the pixel based mapping unit facilitated easier and faster computations of the susceptibility in GIS, however in reality a pixel doesn’t represent morphological changes in the ground. Landslide processes, including the extent of source area and run-out of debris flowslides are highly controlled by the slope features of the terrain (Carrara et al., 1992). In fact, it is relatively easy to visualise and interpret maps in the field if the results are shown within a slope feature bounded by drainage and crest lines. This also helps to use the susceptibility map for other purposes, including the integration of landslide sizes larger than the size of a pixel. For this reason, the study area is partitioned into 2,234 slope-units, which were identified and digitized manually from the topographic map. Each slope unit contains an area bounded by drainage lines, ridge lines or breaks in slope. The average area of a slope unit is about 9,848 m², corresponding to about 99 pixels of 10 m × 10 m. For each slope unit, a single probability value was assigned taken from the predominant probability values of pixels within the slope unit.

5.3.2 Inventory-based method for hazard analysis

Figure 5.9 shows the work flow of the inventory-based approach for landslide hazard estimation. It requires information on two basic parameters:

(1) the landslide susceptible zones: indicating zones with relatively high, moderate and low susceptibility, and

(2) the number and sizes of landslides expected on natural slopes in different return periods, obtained based on a relationship between the number of landslides on cut slopes and the frequency distribution of cut and natural slope failures.
From susceptibility to hazard assessment

To convert the susceptibility map into a quantitative hazard map i.e., the probability of occurrence of a landslide of a given size in a given time period, the following information is required:

1) Information on the number of landslides on natural slopes. The inventory indicates that landslides occur on natural slopes in triggering events that cause many cut slope failures (e.g., in 2006 and 2009). Based on the data of the 2006 and 2009 events, for which a complete inventory was
available for both cut slopes and natural slopes, it is estimated that during such a landslide triggering event about 90% of all landslides will occur on cut slopes and 10% on natural slopes. It is assumed that the number of landslides expected to occur on natural slopes in different return periods can be obtained indirectly if a relationship between the number of landslides on cut slopes can be established for different return periods. This relationship was established using a Gumbel model and the landslide inventory on cut slopes (see Section 5.2.1). Table 5.6 shows the number of landslides expected on cut slopes in different return periods and the derived number of landslides on natural slopes.

2) Information on the size of landslides on natural slopes. The landslides were grouped into different magnitude classes with minimum to maximum landslide volumes ranging from 100 to 1,000 m$^3$ (average=550 m$^3$) for M-II, from 1,000 to 10,000 m$^3$ (average=5,500 m$^3$) for M-III and from 10,000 to 100,000 m$^3$ (average=55,000 m$^3$) for M-IV (Table 4.2). Based on the available inventories the percentage distribution of natural slope failures in M-II, M-III and M-IV classes was 66%, 28% and 6%, respectively. These values were used to estimate the relative frequency of landslide size in different return periods (Table 5.6).

3) Information on landslides in different susceptible zones. The susceptibility map was grouped into three susceptible zones, as high (estimated probability > 0.6), moderate (probability 0.4-0.6) and low (probability ≤ 0.40). For each return period landslides were to be distributed in the three susceptible zones based on the result of the model fitting performance (success rate curve). Finally, hazard or the (spatial) probability of occurrence of a landslide of a given size per pixel for each return period was estimated as the ratio of the total area of landslides of a given size expected in each susceptible zone to the total area of the susceptible zone. For each magnitude class source area of a landslide was obtained by dividing the volume for the given magnitude class with the average depth of the landslide at the scarp. For the magnitude class M-II, M-III and M-IV the average depth of a landslide was taken as 2, 5 and 10 m, respectively. Thus different hazard scenarios can be obtained considering a minimum, average and maximum landslide size of each magnitude class.
Hazard analysis

Table 5.6 Number of landslides expected on natural slopes in different return periods.

<table>
<thead>
<tr>
<th>Return Period</th>
<th>Nr of landslides expected on slopes</th>
<th>Total landslides</th>
<th>Nr of landslides on natural slopes in magnitude class</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cut</td>
<td>Natural</td>
<td>M-II</td>
</tr>
<tr>
<td>5</td>
<td>112</td>
<td>11</td>
<td>123</td>
</tr>
<tr>
<td>15</td>
<td>195</td>
<td>20</td>
<td>215</td>
</tr>
<tr>
<td>25</td>
<td>230</td>
<td>23</td>
<td>253</td>
</tr>
<tr>
<td>50</td>
<td>279</td>
<td>28</td>
<td>307</td>
</tr>
</tbody>
</table>

A is based on Gumbel analysis.
B is calculated as 10% of A and rounded.
C, D and E are 66%, 28% and 6% of B, respectively.

5.3.3 Results

5.3.3.1 Temporal probabilities of landslide events

Table 5.7 shows the exceedance probability for the occurrence of one or more landslide events in the four sections over a time period of 1, 3, 5, 15, 25 and 50 years as estimated using Eq. (4.3). After 25 years all sections will have the maximum probability of exceedance of rainfall threshold \( P(R > R_T) = 1 \) and thus have the highest probability (0.73) of experiencing one or more landslide events that can trigger one or more landslides. The results indicate that sections I and III, and sections II and IV have the same mean recurrence interval of the threshold and thus the temporal probability is also similar. The probability of one or more landslide events to occur in one to 50 years time varies from 0.13 to 0.73 in different sections. Section I and III show a relatively high temporal probability of exceedance and they also have maximum incidences of recorded landslides. The obtained estimates will be used to quantify landslide hazard. The obtained threshold model is validated using landslide events of 2009 (see Section 7.2, Chapter 7).

Table 5.7 Temporal probability of landslide events (Threshold: \( R_T = 210 - 0.54 R_{sed} \)).

<table>
<thead>
<tr>
<th>Area (section)</th>
<th>( R &gt; R_T )</th>
<th>Temporal probability over different time intervals</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>nr</td>
<td>1yr</td>
</tr>
<tr>
<td>Burtiyear      (I)</td>
<td>11</td>
<td>0.37</td>
</tr>
<tr>
<td>Hillgrove      (II)</td>
<td>3</td>
<td>0.13</td>
</tr>
<tr>
<td>Marapallam     (III)</td>
<td>11</td>
<td>0.37</td>
</tr>
<tr>
<td>Runnymede      (IV)</td>
<td>3</td>
<td>0.13</td>
</tr>
</tbody>
</table>

\( R_T \) is the threshold value of rainfall \( R \).
5.3.3.2 Landslide susceptibility map

Figure 5.10 shows the probability map obtained by the logistic regression analysis. The susceptibility is expressed in terms of the estimated probability of a landslide occurring in a pixel under the given geo-environmental conditions. About 25% of the unit areas (5.5 km²) have an estimated probability of more than 0.6 and can be viewed as highly susceptible to landslides. Most high susceptible areas are located north of Katteri, NW of Burliyar and around drainages where torrent streams can result in debris slides.

![Estimated spatial probability map](image)

**Figure 5.10** Map showing the estimated spatial probability of landslides obtained using logistic regression analysis.

Table 5.8 shows the results of the error matrix for the logistic regression model shown in Figure 5.10. The error matrix figures represent a measure of the "overall goodness of fit" of the susceptibility model (Guzzetti et al., 2006). The model has correctly classified about 74% of the mapping units in either stable or unstable groups. It has also correctly classified about 71% of the unstable areas but misclassified about 29% of the landslide units to the stable group. About 26% of the mapping units that are now free of landslides were classified as "unstable" by the model. These can be viewed as areas that have environmental conditions typical of unstable slopes and could be the source of future landslides. The misclassified 29% of landslide units as stable group could be the areas of old landslides which were not recorded in the historical records, but in any case such areas needs detail site-specific investigation.
Table 5.8 Error matrix: comparison between mapping units classified as stable or unstable by the LR model and mapping units free of and containing landslides in the inventory map.

<table>
<thead>
<tr>
<th>Actual Groups (inventory)</th>
<th>Predicted groups (model)</th>
<th>Stable group</th>
<th>Unstable group</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stable mapping units free of landslides in the inventory</td>
<td>74%</td>
<td>26%</td>
<td></td>
</tr>
<tr>
<td>Unstable mapping units containing of landslides in the inventory</td>
<td>29%</td>
<td>71%</td>
<td></td>
</tr>
</tbody>
</table>

Overall percentage of mapping units correctly classified = 74%.

The success rate curve (Figure 5.11) shows that 80% of all landslide source areas are predicted by 28% of the classes with the highest value in the susceptibility map. Most of the landslides shown in the inventory map are in areas classified as susceptible by the model, and only 10% of the slope failures are in areas classified as low susceptible (probability ≤ 0.40) by the model. The corresponding model fitting performance is 73% for high, 17% for moderate and 10% for low susceptible zones.

Table 5.8 and Figure 5.11 clearly indicate that the logistic model has performed well in classifying the susceptible areas. About 70% of the landslides occur within areas having membership probability > 0.6 (Figure 5.11) and this can be viewed as a measure of the probability of occurrence of future landslides in a given area. Since the landslides are individually small and are first-time failures, therefore, for the hazard calculation based on the threshold approach, the probability estimated by the model was taken as the measure of the (spatial) probability of future landslides at each pixel, as used in Guzzetti et al. (2005).

Figure 5.12 shows the spatial probability map after up-scaling the pixel-based mapping unit (Figure 5.10) to the slope facet-based mapping unit. The up-scaling has resulted in differences in the total percentage area of different susceptibility classes shown in Figure 5.10. After up-scaling, about 18% of the unit areas has an estimated probability of more than 0.6 and 73% areas are now classified as weak or low susceptible. About 10% of areas initially classified as moderate or high susceptible is now grouped as low susceptible. These moderate or high susceptible areas are those that are located adjacent to the drainage and fall into slope-units whose majority of the unit area i.e., areas above the drainage is being characterized as low susceptible.
Figure 5.11 Graph showing success rate curve (model fit). The x-axis of the graph shows the percentage of map with highest probability values and y-axis shows the percentage of landslide area in each susceptible classes.

Figure 5.12 Landslide susceptibility map showing estimated spatial probability values per slope-unit.

5.3.3.3 Threshold-based landslide hazard

Figure 5.13 shows examples of the threshold-based landslide hazard map obtained using Eq. (5.6). The Figure portrays landslide hazard for slope units
located west of Burliyar for six periods (1, 3, 5, 15, 25 and 50 years), and for two landslide volumes (larger than 1,000 m$^3$ and 10,000 m$^3$). The joint probability in the Figure 5.13 indicates that a slope-unit will be affected by future landslides that exceed a given volume, in a specified time period, and due to the local environmental setting. For a one year time interval the hazard probability indicates the probability of occurrence of at least one landslide in a year. A total of 12 landslide hazard maps were generated each representing a specific scenario i.e., a specific time span and a landslide size.

Table 5.9 shows the percentage distribution of the study area in different hazard classes in different time periods. The percentage distribution is similar from 25 years onwards because of similar temporal probability values for larger time periods. As expected with the increase in time periods the percent area in the hazard classes with higher probability value also increases. For landslides with a size $\geq 10,000$ m$^3$ the percentage area is distributed in the range 0.001-0.01 whereas for $\geq 1,000$ m$^3$ the distribution is up to 0.01-0.1. This differences is due to the low exceedance probability of large landslides ($P_M = 0.01$) in comparison to small landslides ($P_M = 0.07$) given the landslide triggering rainfall event. In other words, the probability of occurrence of relatively larger landslides is lower than smaller landslides in a given time period. It is to note that though some areas have very high spatial probability ($P_S > 0.8$) but the maximum joint probability obtained is less or equal to 0.1. The hazard value in a slope-unit is equal to $P_S$ value only in cases when $P_T$ and $P_M$ are equal to 1 and the hazard probability becomes zero if any of the probability i.e., $P_S$, $P_T$ and $P_M$ takes zero value e.g., in a section if $P_T$ is high but $P_S$ of a slope-unit is 0 then the estimated hazard of the slope-unit is zero.

5.3.3.4 Inventory-based landslide hazard

From the obtained susceptibility map (Figure 5.10) and the three magnitude classes (M-II, M-III and M-IV) a total of nine hazard scenarios were generated for each return period by considering the minimum, average and maximum landslide size in each magnitude class. Table 5.10 gives an example of the hazard probability calculated for a scenario of a 50-year return period and M-II minimum magnitude class following the method given in Section 5.3.2. For the nine scenarios the hazard probability per pixel varies from 0.000002 to 0.0022. The highest probability value was obtained for the high susceptible zone for scenario considering M-IV max landslides and a 50-year return period.
Fig. 5.13 Examples of landslide hazard maps for 6 periods, from 1 to 50 years, and for two landslide volumes, $V_L \geq 1,000$ m$^3$ (A) and $V_L \geq 10,000$ m$^3$ (B). The probability gives the joint probabilities of landslide volume, of landslide temporal occurrence, and of landslide spatial occurrence.
Hazard analysis

Table 5.9 Percentage of the study area in different hazard classes.

<table>
<thead>
<tr>
<th>Time period (year)</th>
<th>Landslide volume (m³)</th>
<th>% area in different hazard classes (probability)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0-0.0001</td>
<td>0.0001-0.001</td>
</tr>
<tr>
<td>1</td>
<td>≥ 1,000</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>≥ 10,000</td>
<td>33</td>
</tr>
<tr>
<td>3</td>
<td>≥ 1,000</td>
<td>23</td>
</tr>
<tr>
<td></td>
<td>≥ 10,000</td>
<td>30</td>
</tr>
<tr>
<td>5</td>
<td>≥ 1,000</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>≥ 10,000</td>
<td>29</td>
</tr>
<tr>
<td>15</td>
<td>≥ 1,000</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>≥ 10,000</td>
<td>28</td>
</tr>
<tr>
<td>25</td>
<td>≥ 1,000</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>≥ 10,000</td>
<td>28</td>
</tr>
<tr>
<td>50</td>
<td>≥ 1,000</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>≥ 10,000</td>
<td>28</td>
</tr>
</tbody>
</table>

Table 5.10 Example of the hazard probability calculation for a 50-year return period for landslides of a size M-II min.

<table>
<thead>
<tr>
<th>Magnitude class</th>
<th>Susceptible zone</th>
<th>Nr of pixel</th>
<th>Model fitting performance (success rate)</th>
<th>Nr of landslides on natural slopes in magnitude class M-II (see Table 5.6)</th>
<th>Hazard probability at each pixel</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>A</td>
<td>B</td>
<td>C</td>
<td>D=0.5 IIC H B/A</td>
</tr>
<tr>
<td>M-II min.</td>
<td>High</td>
<td>54,184</td>
<td>0.73</td>
<td></td>
<td>0.00012</td>
</tr>
<tr>
<td></td>
<td>Moderate</td>
<td>27,170</td>
<td>0.17</td>
<td></td>
<td>0.00006</td>
</tr>
<tr>
<td></td>
<td>Low</td>
<td>137,929</td>
<td>0.10</td>
<td></td>
<td>0.00001</td>
</tr>
</tbody>
</table>

* landslide area (nr of pixel) taken for the analysis for M-II min having volume =100 m³

5.4 Assessment of landslide run-out distance

For the analysis of run-out distances, 55 debris slides and debris flowsides that occurred between 1978 and 2004 within and adjacent to the study area were selected. The data were obtained from various reports available in the Geotechnical office at Coonoor. For the selected landslides, data on the run-out distance, landslide width and depth, and land use were available. The run-out distances varied from 10 to 1,000 m. The volume of landslides was estimated based on the description of landslide morphology (length, width and depth) given in the reports.

In order to calculate the run-out distance for a specific landslide magnitude class, an empirical relationship was established between the landslide volumes and the run-out distance in the Nilgiri area. Figure 5.14 shows the
scatter plot taking the log of landslide volumes on the x-axis and run-out distance on the y-axis. The distribution has a positive power fit with scaling exponent as 0.55. The relation can be expressed as:

\[
Rd = 1.0 \times V_r^{0.55} \quad \left( R^2 = 0.84, n = 55 \right)
\]  

(5.9)

where \(Rd\) is the run-out distance, \(V_r\) is the volume and \(n\) is the total number of landslides taken in the analysis. Run-out distance was estimated for the minimum, average and maximum landslide volume of each magnitude class (Figure 5.14). The maximum run-out distance for landslides of magnitude class M-II, M-III and M-IV was estimated to be 45, 160 and 560 m, respectively using Eq. (5.9).

The run-out model does not provide direct information on the intensity or destructive power of a landslide, however intensity can be inferred qualitatively as a function of landslide volume and landslide velocity (Cardinali et al., 2002). The steepness of the flow path can be used to infer velocity and landslides can be grouped into different intensity scale as suggested by Cardinali et al. (2002). But, since nearly all landslides are translational occurring on steep slopes the run-out will be fast, and therefore in this study run-out with different velocities were not differentiated. Also, the run-out model does not provide information on the total deposition area of a landslide and therefore it may not be applicable for assessing vulnerability and risk to areas likely to be inundated by debris.

In the run-out analysis landslides with a volume less than 100 m³ were not considered because these occur mostly on cut slopes along the transportation lines and have very low run-out.

### 5.5 Discussion and conclusions

#### 5.5.1 Landslide hazard along the road and railroad

Given the completeness of the historical landslide information especially along the railroad for the past 21 years, I was able to apply a landslide hazard assessment method that is based only on the historical information, without including statistical analysis of possible contributing factors or carrying out physically based modelling.
The proposed method allowed us to determine quantitative landslide hazard along a road and a railroad estimated directly from the frequency of past slope failures. In fact, landslide hazard assessment approaches using frequency of past landslides not necessarily require prior landslide susceptibility analysis if a complete inventory is available (Corominas and Moya, 2008). In such cases, the probability of occurrence of landslides in a given area can be estimated directly from the past landslides, especially when we are interested to know the hazard over particular sections of the (rail) road and not for every location individually.

According to the definitions given by Varnes (1984), the landslide hazard should provide information on the probability of occurrence of landslides and their magnitudes in a given area. Along a transportation line such as a road or railroad this definition of hazard is more appropriate if it includes information on the probability of occurrence of a certain number of landslides of a given size over a given unit length (e.g., per kilometer section). The number of landslides is required if direct risk to road, vehicles, commuters and the indirect risk due to traffic disruption is to be analyzed. The number of landslides per unit length can provide the estimate of the probability of a landslide hitting a vehicle (AGS, 2000; Wilson et al., 2005) and if it is multiplied by the probability that the landslide will be of a given volume then
the total volume of landslide deposits expected and the time required to remove the debris can be estimated.

The present method therefore defines hazard in terms of the number of landslides expected in a given location (per kilometer) and its annual probability of occurrences (inverse of the return period). This method will help to quantify the direct and indirect risk in terms of the annualized loss or the total annual loss.

In landslide modelling, the Gumbel model has been used to analyse the frequency of extreme events in spite of certain limitations and assumptions, of landslides being stochastic processes and random distributed independent events, as discussed by Miller (1988) and Odorico and Fagherazzi (2003). These assumptions should be considered when interpreting and using the results of the probability model. In this study, the use of Gumbel model was found suitable for estimating the frequency of slope failures that are small in size and occur repeatedly from cut slopes at a number of locations.

It is important to realize that extrapolation of the return periods based on the Gumbel analysis should be limited to a maximum of twice the length of the available time series. However, if the inventory does not contain recorded events that are related to much larger return periods, then one should be careful with extending the time of prediction too far. In this analysis, I estimated the probability only up to 50 year return period, which is slightly more than twice the record length available for the study. The records also indicate that landslides occur frequently in the area and therefore it was prudent here to consider scenarios based on lower return periods i.e., 1, 3 and 5 years.

The result of the Gumbel analysis is also prone to uncertainty. The degree of uncertainty can be low if the inventory contains records for all landslides such as those available for the railroad. The availability of a substantially complete inventory along the railroad provided a better assessment of the frequency of slope failures. Along the road it was not possible to perform a Gumbel analysis for every kilometer section because of the incompleteness of the landslide records. However, at this stage the results of the analysis along the road can be acceptable because the inventory at least contains large and damaging landslides.

Any change in the intensity of rainfall due to the local orographic affect can induce uncertainty in the result of the hazard analysis. A very high rainfall occurring at certain sections of the road and the railroad may trigger more
Hazard analysis

landslides locally. The average rate of occurrence of extreme events might be increased due to climate change, however this has not been proven yet for the area based on historical rainfall records.

The results of the hazard assessment are also prone to uncertainty due to the non-cyclical nature of landslide events. The 50-year return period (i.e., the number of landslides that will occur on an average once in 50 years) may occur next year or not for 100 years or may be exceeded several times in the next 50 years. Slopes that are subjected to landslides once might behave differently under similar rainfall conditions. Also human intervention along the (rail) road in the form of the construction of retaining walls, and drainage works, will have an influence. The rainfall event with a 50-year return period (i.e., as characterized by the number of landslides per kilometer caused by this event) may cause less landslides when it happens later again.

The inclusion of the proposed magnitude class in the hazard assessment will help in assessing landslide risk along the road and the railroad. Ideally, magnitude should be quantified based on absolute values of landslide velocity, intensity, impact pressure, etc. but such parameters are very site specific and difficult to obtain and integrate in the hazard analysis. Due to this limitation and the complexity of landslide phenomena, use of the proposed magnitude classification is considered the best solution for this study.

In previous chapter (Chapter 4), I estimated the temporal probability of occurrence of one or more rainfall events that can trigger landslides along the transportation lines, based on rainfall thresholds. However, such an analysis does not provide information on the frequency of landslides in different sections of the road and the railroad. The method presented here does allow us to make an estimation of the expected number of landslides per unit length and return period.

This study aimed to quantify landslide hazard along a transportation corridor where landslides are small in size but occur frequently. Hazard assessment including small-sized landslides is important if these occur along roads and railroads, as even small slips can result in an accident. Temporal prediction of few small-sized slides in a given area is difficult, but in the Gumbel extreme value method, it is possible to estimate the probability of occurrence and return period of the larger (extreme) events based on past records. This information will help to manage landslide risk more rationally.
5.5.2 Landslide hazard for natural slopes

The proposed threshold-based and the inventory-based method allowed us to determine quantitative hazard of first-time slope failures in a data scarce inventory. Since the inventory is incomplete and the landslides are small and non-repetitive therefore the traditional method of computing the frequency of slope failures based on the recurrence of landslides was not applicable in this case. Given the incompleteness of the historical landslide data for the natural slopes, the limited availability of information on rainfall and the date of occurrence of landslides, the estimation of the probability of occurrence of landslides and the calculation of hazard was still feasible with the proposed methods, which was otherwise difficult. Therefore, most of the landslide hazard models presented in the literature are actually susceptibility models providing an estimate of ‘where’ landslides are expected, rather than giving also temporal and size probability (Brabb, 1984; Guzzetti et al., 2005).

The susceptibility model used to predict the spatial probability of potential landslides is based on certain assumptions. It is assumed that landslides will occur in future under the same conditions and triggering factors that produced them in past. One has to take into account that geo-environmental conditions of an area such as land use or hydrological conditions may change due to human action. Conditions may also change when the source of a landslide is exhausted by earlier landsliding or the morphology of the slope is changed and becomes stable (Guzzetti et al., 2005). However, I would like to state that to some extent the assumption holds true for the study area. The preparatory factors (e.g., aspect, slope and regolith thickness) are not expected to change significantly in a short time period, say in a 50 year time. Local morphological changes may occur due to landsliding but this will not substantially affect the susceptibility model because most landslides on natural slopes are first-time failures. Also the land use has been rather static, and the total area of the reserved forest and tea estates, which cover about 90% of the area, have not changed for the past 100 years except for a limited human interference near the Katteri area.

In the threshold-based hazard approach, the temporal probability of landslides was estimated indirectly from landslide events using the mean rate of occurrence of the threshold rainfall. In the Nilgiri area all landslides are rainfall induced and occur mostly during October to December due to the retreating monsoon. However, a very high rainfall occurring due to some local phenomena may affect the distribution of landslide events in the area. The temporal probability gives the probability of occurrence of one or more landslide events in a particular area in a given time period. As expected the probability increases with the increase in the length of the time period such
Hazard analysis

that the maximum value (0.73) is reached for a 25 year period. In more than 25 years time it is always certain to have at least one landslide event. Here the highest probability is 0.73 and not 1 because it was shown that all rainfall exceeding threshold value do not trigger landslides rather the success is only 0.73 i.e., 73% of cases the rainfall triggers landslides if exceeded. Due to the possible gap in the record, I have taken 0.73 as the success of the threshold model for triggering landslides on the natural slopes.

For the threshold modelling, I considered all landslide events irrespective of the number and sizes of landslides they triggered. The temporal model can be improved further if the threshold can be generated separately for different landslide sizes and landslide densities, but such an exercise requires a more detailed landslide and rainfall inventory, and for a long time period. Substantially complete event-based landslide inventories along with known dates of landslide events are seldom available particularly for past dates.

Guzzetti et al. (1999) proposed to include landslide magnitude, as a proxy for landslide damage (destruction), in the hazard analysis to complete the definition of hazard given by Varnes (1984). Damage caused by a landslide largely depends on the intensity and kinetic energy of the flow. For a catchment scale study these parameters are extremely difficult to obtain and to integrate in the hazard zoning. Since information on landslide volume is difficult to obtain if the inventory is prepared from remote sensing data, and therefore the landslide area is commonly used as a proxy for landslide magnitude (Guzzetti et al., 2005). In this study, the availability of data on volume allows using it as a proxy for landslide magnitude, which is the better measure of landslide destructiveness.

The assumption that the three probabilities i.e., the probabilities of landslide volume, the temporal probability of landslide event and the spatial probability of slope failures are independent is necessary to make the multiplication of the three probabilities statistically feasible. To some extent the assumption may be true for this case study. The temporal probability is based on rainfall, which is the main trigger of landslides in the area. For the threshold analysis, I have considered all landslide events irrespective of the number of landslides they triggered and the spatial distribution of landslides. Therefore, the threshold is not directly dependent on a particular terrain condition within the study area. Further for the susceptibility modelling, I did not consider rainfall as a factor or landslides related to a specific rainfall event, rather I considered all landslides in the study area as a dependent variable. Therefore, it is reasonable to accept that both spatial and temporal probabilities of landslides are independent.
In nature the number of landslides and the proportion of large to small landslide volume can vary according to the intensity of rainfall. It is expected that a very high intensity rainfall much above the threshold value can trigger more landslides and of a larger volumes than a rainfall of relatively low intensity. Thus, both rainfall and frequency-size distribution of landslide are mutually dependent. On contrary, in this case study it is observed that a very high rainfall event of 2009 resulted in less landslides and of relatively smaller volumes than in 2006 (dealt in Chapter 7). This difference is mainly because of the contrast in the terrain condition where most landslides have occurred in 2006 and 2009. Landslides in 2006 occurred on relatively steeper slopes than in 2009. Thus, I can say that the frequency-size distribution of landslides is not totally dependent on the rainfall condition rather it is also related to the terrain type. However, in other studies, based on a handful of complete inventories, researchers (e.g., Guzzetti et al., 2002; Malamud et al., 2004) have demonstrated that the probability density of landslide size on natural slopes does not change significantly with changing physiographical conditions. Malamud et al. (2004) showed that the probability density distribution are virtually identical for landslides triggered by three different triggers in three different physiographical regions (e.g., co-seismic landslides in southern California, rainfall induced landslides in Guatemala, Central America and landslides due to rapid snow melting in Umbria, Italy). For simplicity, like other studies, I also assume that the probability distribution of the landslide size on natural slopes is independent of the terrain type.

In this study, I have noticed that relatively high susceptible areas (e.g., east of Burliyar) can be of low hazard in a given time if the rainfall does not exceed the threshold value (e.g., 2009 event east of Burliyar) or vice versa. The hazard of an area is therefore conditionally dependent on the probability of occurrence of a landslide triggering rainfall event and the susceptibility of the terrain. However, due to the difficulty in evaluating conditional probabilities its multiplication remains the best option to evaluate hazard. The model can be further improved when better ways of generating more accurate measures of the thematic variables and hazard model become available. One way to improve a hazard model is to incorporate event-based landslide inventories and make separate spatial probabilities, temporal and size probabilities per return period of the triggering event that caused the event-based landslides (e.g., Glade, 2001). But as a major drawback the event-based landslide inventories of multiple dates and of very long time period are seldom available.

The parameters used to estimate threshold-based landslide hazard are not precise and contain a considerable degree of uncertainty. The degree of
Hazard analysis

Uncertainty increases with every addition of input parameters: from landslide mapping towards hazard. Though it is difficult to quantify uncertainties it is possible to outline the important sources of uncertainties for a better understanding and interpretation of hazard.

For the hazard analysis, I assumed that the probability distribution of landslide size will not change over time and within the study area. Though it is shown elsewhere that magnitude probability does not change significantly over time and area (Malamud et al., 2004; Guzzetti et al., 2005) but there is always an uncertainty associated with this assumption because on cut slopes the size probability is observed to vary according to the rainfall and area (see Section 4.3.3). Significant increase or decrease in the probability value will affect the hazard and the percentage distribution of the study area in different hazard classes.

Uncertainty is also associated with the spatial occurrence of first-time slope failures because the threshold itself does not give indication of the precise location of future landslides. Even within the same susceptible areas rainfall can trigger landslides on one slope and not on others located nearby. This uncertainty is due to the fact that there are other landslide initiating agents (e.g., pore water pressure, shear properties of soil, etc.) which locally influence slope failures but are not considered in the statistical modelling.

For the calculation of the temporal probability of landslides the value of $P[L|R > R_T]$ is taken as 0.73 in all sections, which is based on the result of the frequency analysis of landslide events along the railroad. This value of $P[L|R > R_T]$ resulted in the temporal probability of 0.73, which is the maximum probability value used in the analysis even when the exceedance probability is 1. Thus, even when there is a certainty of a rainfall exceeding the threshold value but there is always an uncertainty of the actual occurrence of landslides irrespective of the time period.

Carrara et al. (1992) have shown that uncertainty is associated with all factor maps used in a hazard modelling. Uncertainty is very high in a landslide inventory map even if it is prepared from high resolution aerial photos. Carrara et al. (1992) demonstrated an error of more than 50% when two inventory maps of the same area but prepared by different experts are compared. In this case study, since the inventory is prepared from historical records where the spatial location and size of landslides are inferred therefore a substantial uncertainty is incorporated particularly for slides which are not properly described in the records. Another source of uncertainty is associated with the occurrence of future landslides within a slope-unit. Each slope-unit
on average contains 100 pixels of 10 m × 10 m size and is represented by a single spatial probability value assigned after up-scaling the pixel based susceptibility map. If the slope-unit is assigned low spatial probability value but contains few pixels of high probability values then the presence of latter induces uncertainty in the actual hazard. However, this uncertainty can be minimised if the average area of slope units is further reduced.

The spatial probability used in the threshold-based hazard is actually the membership probability of a pixel obtained by the logistic regression model. The probability indicates the likelihood of producing a landslide under the given geo-environmental condition. However, this in combination with the temporal probability of landslide events for a specified time period, can be used as a powerful guide to decide on the future development (Crozier and Glade, 2005).

In case, if landslide hazard identification is carried out with an aim to scope the nature of the potential threat to elements at risk then the (spatial) probability of occurrence of landslides has to be estimated as presented in the inventory-based hazard method. This probability depends on the number and sizes of landslides expected in future. For example, the estimated probabilities for a single future landslide in the area will be much smaller than for 1,000 future landslides (Chung and Fabbri, 2005). Thus, the estimated hazard is highly sensitive to the number and the sizes of future landslides.

Medium to very high uncertainty is associated with the inventory-based hazard estimation and this is due to the limitation of the model, its basic assumption, scale of the study and availability of data. The use of return periods introduces a high uncertainty in the analysis mainly due to the limited time period of the landslide inventory (21 years). Therefore the effect of landslide events with larger return periods cannot be properly evaluated. High uncertainty is associated with the probability of occurrence of landslides. Since I derived the number of future landslides on natural slopes indirectly from a Gumbel analysis, which was originally performed on cut slopes, therefore the uncertainties associated with the Gumbel model such as the non-cyclical nature of landslide events, extrapolation of the time period, etc. also hold true for this case.

The assumption that for a given event 10% of landslides will occur on natural slope may not hold always and everywhere. However, in this case the assumption may be true because it was based on the two events which are representative of the study area. The 2006 event triggered most of the
Hazard analysis

landsides east of the Hillgrove whilst the 2009 events affected areas west of the Hillgrove (refer Chapter 7).

The proposed hazard models are based on a limited set of landslide data. When new information on landslides becomes available, the hazard model can be improved. The models can be used to estimate hazard for any time period to provide quantitative expertise on future slope failures to planners, disaster management authorities, decision makers and individual landowners. The models provide information on the likelihood of the initiation of future slope failures in an area and not the area that are likely to be inundated by debris. For the latter case run-out areas are needed to be incorporated before using the model for risk analysis. For this study, I have generated limited hazard scenarios, however depending on the need more hazard scenarios can be obtained using different landslide magnitude probabilities.

5.5.3 Landslide run-out distance

The JTC-1 guidelines (Fell et al., 2008) recommend providing description of landslide travel distance in the susceptibility or hazard map, in order to access risk to areas located below the landslide initiation zones. To provide information on run-out distances, a simple empirical relation with volumes based on historical events in the area were obtained without taking into account many other factors that might play a role.

The model has certain limitations such as the issue related to the maximum travel distance considered in the analysis obtained based on Eq. (5.9) and the actual travel distance measured in the field. For example, landslide sizes with a volume 1,000 m$^3$ and 10,000 m$^3$ have the maximum measured run-out distance of 60 and 200 m, respectively as shown in the scatter plot in Figure 5.14. But, in the analysis I have taken these values as 45 and 160 m as estimated using Eq. (5.9). Since the run-out hazard also depends on the maximum run-out distance, therefore a certain degree of uncertainty is induced due to the estimated value, which is lower than those measured in the field. To estimate the maximum hazard, the maximum run-out values can be considered, however, due to the large variation in the measured run-out distances it was reasonable here to consider the best-fit value.
Chapter 6: Landslide risk analysis

Landslide risk is defined as the expected number of lives lost, persons injured, damage to properties and disruption of economic activities due to landslides for a given area and reference period (Varnes, 1984). In the study area landslide losses are both direct, affecting the alignment, vehicles, buildings, cultivated lands and people, and indirect by disrupting the economic activities.

In this chapter an approach to estimate both direct and indirect risk along transportation corridors will be presented. The historical data will be used to estimate vulnerability of elements at risk and examples of risk estimation along the transportation lines will be presented, including: (i) the direct risk to the infrastructural properties, moving vehicles and commuters, and (ii) the indirect risk due to the traffic disruption. For natural slopes an approach to estimate risk in a data scarce inventory will be presented where risk to elements at risk located in the initiation areas of potential landslides and within the run-out path of landslides will be estimated by incorporating run-out distance in the risk analysis.

6.1 Introduction

Landslide is one of the major natural risks in the Nilgiri hills. To reduce the disastrous impact of landslides on society and to facilitate a rationale for land use planning, landslide risk quantification forms a fundamental tool in risk management process (Fell et al., 2005, 2008). Estimation of risks associated with landslides, therefore, becomes important in developing proper disaster management policies.

The landslide risk definition given by Varnes (1984), which includes loss to properties and lives and disruption of economic activities, is very appropriate for a transportation corridor where the risk is both direct, affecting the properties and people, and indirect, disrupting economic activities. Direct risks are the cost for restoration and repair of infrastructure, damages to building and vehicle, loss to cultivated land and loss of lives, whereas indirect risk affects the society by disrupting the utility services and local businesses, thereby incurring loss of revenue, tourism and increase in cost of day to day commodities (van Westen et al., 2006).

Although landslide risk was already defined by Varnes in 1984 the quantitative estimation of risk remains a difficult task due to problems in quantifying the individual components of the risk equation (Fell et al., 2005; van Westen et al., 2006). To quantify risk a number of different parameters
Landslide Risk assessment

are required, which are often difficult to obtain. It requires estimation of the vulnerability of elements at risk resulting from the specified landslide magnitude, and the spatial and temporal probabilities that a given element at risk is hit by a landslide of a particular type and magnitude (AGS, 2000; Fell et al., 2008). This concept of landslide risk is well documented and several publications are available that deal with the concepts and possible methods to carry out risk analysis (e.g., Guzzetti, 2000; Dai et al., 2002; van Westen et al., 2006; Fell et al., 2008), but the number of publications on the actual implementation of direct and indirect landslide risk estimation is still rather modest. Van Westen et al. (2006) highlighted some of the challenges in quantitative risk analysis related to the unavailability of a complete landslide inventory for the quantification of frequency of slope failures, the difficulty in incorporating landslide run-out for all landslide susceptible areas and the difficulty in assessing vulnerability of elements at risk due to insufficient damage data. Lack of a uniform methodology for the assessment of the vulnerability of dynamic and static elements at risk makes risk analysis further difficult (Glade and Crozier, 2005).

The estimation of risk becomes further complicated in many countries due to the insufficient historical records on landslides, unavailability of data on past losses and the uncertainty in the assessment of direct and indirect risks. The estimation of indirect risk is difficult because the loss is not only site specific but affects a larger part of the area far beyond the actual place where the physical damage has taken place (Remondo et al., 2008). The cumulative effect of indirect loss includes all types of losses such as economic loss, social loss and emotional loss, which are difficult to quantify. Such loss is often not directly visible to the society but studies have indicated that if it is estimated realistically then the resulting indirect economic loss would be higher than the direct loss (Schuster and Fleming, 1986; Zezere et al., 2007).

Recently, a number of attempts have been made to quantify direct landslide risk (e.g., Bunce et al., 1997; Hungr et al., 1999; Budetta, 2002; Kong, 2002; Guzzetti et al., 2004; Catani et al., 2005; Wilson et al., 2005; Zezere et al., 2007; Remondo et al., 2008) and indirect risks due to the blockage of roads and railroads (e.g., Remondo et al., 2008; Zezere et al., 2007; Bonachea et al., 2009). Hungr et al. (1999) have used the magnitude-frequency curves of rock falls to assess their direct impact on a moving vehicle. Some researchers have used the “event tree” analysis for risk quantification (Bunce et al., 1997; Budetta, 2002). In the event tree approach an occurrence probability is assigned to each event in a sequence which could lead to a landslide fatality. Some researchers have used annual probability of landslide hazard and related consequences to estimate both
direct and indirect risk due to a landslide (Zezere et al., 2007; Remondo et al., 2008). They estimated consequences as a product of vulnerability and the value of elements at risk.

In all risk studies the assessment of vulnerability of elements at risk remains a difficult task. According to the Joint Technical Committee on Landslides and Engineered Slopes (JTC-1) guidelines (Fell et al., 2008), physical landslide vulnerability is the degree of loss to a given element or a set of elements at risk from the occurrence of a landslide of a given magnitude or intensity. It is expressed in a scale from 0 (no loss) to 1 (total loss). For properties the degree of loss can be expressed as either potential monetary loss or physical loss (structural damage) and can be assessed by comparing the value of damage with the actual value of the property (Alexander, 2005; Remondo et al., 2008). For persons, it can be estimated as the probability that a particular life will be lost (Fell et al., 2008).

Along transportation corridors the elements at risk can either be static such as the alignment itself or dynamic such as commuters and moving vehicles. Their vulnerability depends on many factors, including: (a) type and size of the landslide, (b) its intensity and the way of impact, which defines the degree of damage, (c) resistance of the element against the impact of a landslide, (d) position of the element at risk i.e., at the source or in the path of a landslide, (e) type of infrastructure, (f) speed and type of vehicles, and (g) physical condition of commuters (AGS, 2000; Wilson et al., 2005; Galli and Guzzetti, 2007). For the assessment of vulnerability all these factors should be considered, but as a practical limitation these factors are often difficult to quantify due to the scarcity of good damage records and therefore the assessment of vulnerability remains somewhat subjective (Dai et al., 2002).

Few attempts have been made to quantify vulnerability either qualitatively or quantitatively using the available historical damage information. For example, Finlay (1996) proposed vulnerability ranges for death from landslide debris. The AGS (2000) recommended maximum vulnerability value in the event of complete collapse of a building or the building is inundated with debris and the person is buried. However, building designs and building material have an important influence on survival rates as observed in case of earthquakes (Coburn and Spence, 1992) and therefore building strength should also be taken into consideration in the case of landsliding (Lee and Jones, 2004). Michael-Leiba et al. (2005) made a quantitative estimate of vulnerability for buildings, roads and persons as a function of change in distance from the source of a landslide. Highest vulnerability values were assigned to elements
at risk located within the path of a debris flow (i.e., elements susceptible to proximal debris flows). Galli and Guzzetti (2007) analyzed vulnerability of buildings and roads as a function of landslide area and provided minimum and maximum vulnerability curves. The values were 1 (total loss) for landslides of size ranging from $10^3$ to $10^5$ m$^2$ for buildings and from $10^2$ to $10^5$ m$^2$ for roads. Examples of other case studies of vulnerability factors for buildings and people calculated as a function of landslide volumes or landslide intensity are discussed in Lee and Jones (2004).

In most studies vulnerabilities are assessed considering landslide intensity (e.g., Cardinali et al., 2002; Catani et al., 2005) and considering those landslides (e.g., debris flows) that can hit an element at risk located at some distance away from the landslide source. This is true because most often buildings are constructed on low susceptible slopes and therefore damage is more likely from landslides initiating upslope. However, certain properties such as roads, railroads, plantations, etc. are also vulnerable to landslide initiation. Therefore, both the vulnerability in the initiation area of a landslide and the effect of landslide run-out should be analyzed.

Researchers have expressed risk in different ways such as loss over a specified time period or annual loss, depending on the quality of landslide information, the scale of the study and the aim of the analysis. However, if the analysis is meant for defining risk reduction strategies then it is recommended to express risk as annual loss, in order to be able to carry out a quantitative cost-benefit analysis, and also because quantitative risk acceptance criteria for loss of life are usually expressed in per annum terms (Fell et al., 2008).

For elements at risk located on natural slopes, most often risks are quantified for elements at risk located in the landslide initiation areas, whereas much less work has been done to assess risk by incorporating run-out distance of a landslide (e.g., Bell and Glade, 2004). If an area has a potential for hazardous debris flows then the inclusion of run-out distance is essential in order to evaluate the actual risk. Because of the difficulties in incorporating run-out distances for the many possible landslide initiation areas in a quantitative susceptibility map (van Westen et al., 2006), it is appropriate to use empirical relationships first to identify all hazardous zones likely to affect the elements at risk that are located down slope of the landslide initiation areas and then estimate loss to each element separately.

After the quantification of risk, the estimated risk is evaluated in terms of its associated social, economic and environmental consequences, and finally the
risk assessment is carried out by comparing the output of the risk analysis against values of judgments and risk tolerance criteria to determine if the risks are low enough to be tolerable (Fell et al., 2005). The judgment takes into account the political, legal, environmental, regulatory and societal factors. In some countries, the limit of the tolerable risk for persons most at risk and the societal risk is specified (e.g., AGS, 2000) but, there are no universally established individual risk acceptance criteria and the limits of tolerable risk may vary from country to country (Fell et al., 2005).

### 6.2 Methodology

The approach used to estimate landslide risk along transportation corridors is presented schematically in Figure 6.1. Both direct and indirect landslide risk was analyzed. Direct risk was analysed separately for elements at risk vulnerable to landslides on cut slopes and natural slopes. Indirect risk was estimated only for cut slope failures.

To assess direct risk the following activities are required (AGS, 2000; Fell et al., 2008):

1. estimation of landslide hazard for a specific return period,
2. estimation of run-out distances for potential landslides,
3. mapping and quantification of the elements at risk, number of people and properties (monetary value), and assessment of their temporal and spatial probability to be in an exposed position,
4. assessment of probability of the landslide reaching the elements at risk,
5. assessment of the vulnerability of the elements at risk, in terms of property damage (monetary loss) or loss of life, resulting from the specified landslide magnitudes, and
6. estimation of specific risk for each element at risk for various landslide hazard.

The analysis of indirect risk depends on the socio-economic condition of the area of interest. It requires determination of the most important elements and activities in the area and how they could be affected due to the disruption (Remondo et al., 2008). The elements that are indirectly affected due to the traffic disruption include local businesses, residents, tourists, and transport and railway department.

As a first step of the risk analysis, specific risk is estimated individually for each element at risk for a specific landslide hazard and then total risk is calculated by adding all the specific losses of both direct and indirect risks, separately for the property loss and the loss of life.
6.2.1 Assessment of landslide hazard

The method used to estimate hazard along the road and railroad from cut slope failure is described in Section 5.2. A total 18 hazard scenarios were obtained using combinations of the three magnitude classes (M-I, M-II and M-III) and six return periods (T1, T3, T5, T15, T25 and T50 years), see Section 5.2.2.3. These hazard scenarios were used to quantify direct and indirect risks along the road and railroad.

The method used to estimate landslide hazard on natural slopes is described in Section 5.3.2. A total of nine hazard scenarios were generated for each return period by considering the minimum, average and maximum landslide size in each of the three magnitude classes (M-II, M-III and M-IV), see Section 5.3.3.4. These hazard scenarios were used to quantify direct risks to elements at risk located in the initiation area and within the run-out distance of a landslide initiating on a natural slope.
6.2.2 Estimation of run-out risk

The method used to estimate landslide run-out distance is described in Section 5.4. The following section describes the method of how the run-out information is used to estimate landslide risk.

The information obtained from Figure 5.14 can be used to estimate risk considering the run-out distance of potential landslides of a given size located upslope of existing elements at risk. The method used to calculate risk by taking the run-out distance is demonstrated in Figure 6.2. The figure shows the location of an element at risk (a house) relative to the run-out distances of different magnitude classes and landslide hazard zones. At first, from the position of the element at risk run-out distances of different landslide magnitudes are drawn upslope following the maximum gradient. Based on the relation shown in Figure 5.14 landslides that are expected to reach the element at risk initiating from the three landslide hazard zones are selected for the risk analysis. For example, as shown in Figure 6.2 from the high and moderate hazard zones only a landslide of magnitude M-IV avg. and M-IV max. reaches the house located down slope because the house is located within the run-out distance of the two landslides (M-IV avg. and M-IV max.). In contrast landslides of magnitude class M-II and M-III reach the house only if they originate from the low hazard zone. By performing a similar analysis risk can be estimated for all element or group of elements at risk considering the run-out of potential landslides of a given size.

The run-out risk has to be estimated manually for each element at risk, by overlaying buffer distances upslope of the element at risk with the landslide initiation hazard zones.

6.2.3 Assessment of vulnerability of elements at risk

The important elements at risk present in the study area include buildings and their inhabitants, tea/coffee and horticulture plantations, transport infrastructures, vehicles and commuters. The spatial distribution of buildings, plantation areas and transport infrastructures were mapped on 1:10,000 scale from high resolution (2.5 m) Cartosat-1 data of April 2007, a topographic map and field surveys. An inventory containing details of each element at risk was prepared based on consultations with both local inhabitants and institutions (private and government), including tea estates, railway and highway offices. During the field surveys, 175 families were interviewed and questions were asked pertaining to their livelihood (business and income), physical status (i.e., health), family details (number of persons,
age, sex, school or office working time), value of the property and any information regarding previous landslide damages to their properties.

Figure 6.2 Schematic diagram depicting the method used to estimate risk using the run-out distance. The figure shows the location of a house relative to the run-out distances of different magnitude classes and landslide hazard zones.

Buildings were mapped as individual units or as a cluster (in case of small buildings) and digitized as polygons. The polygon map showing the spatial distribution of all building units (Figure 6.3), including houses, offices, shops, factories, hospitals, schools, hotels, mosques and temples, was connected to an attribute table including type of building, number of floors, property value, etc. Houses, offices and shops constitute about 90% of mapped buildings. Property values, including values of house-hold materials, for individual houses, shops and factories were estimated in consultations with the owners of the property, and economic values of other buildings were obtained from data provided by different offices such as the railway and the revenue offices.
The area has three settlements, named Gandhipuran, Burliyar and Katteri, and in the rest of the areas residential buildings are located within the tea estates. Most residential buildings have a single storey with or without column structure and are made of either tin, brick in mud, brick in cement or reinforced concrete.

The tea/coffee and horticulture plantations are the main land use types, and transport infrastructures (road and railroad) are the main transportation lines used by tourists and local inhabitants for travelling in and out of Coonoor.

Figure 6.3 Location of the elements at risk.

6.2.3.1 Vulnerability of plantations

Vulnerability of tea/coffee and horticulture plantations was estimated as the fraction of loss in the production as a consequence of a landslide of a given size. The loss is estimated per pixel area for plants located in the initiation area of a landslide on a natural slope. In the initiation area a small landslide (e.g., magnitude class M-II) will leave many of the plants intact (as can be seen in Figure 6.4A) and therefore per unit area (e.g., a 100 m² area) only a certain percentage of the plants will be destroyed. If the landslides become bigger (M-III and M-IV), then there will be more destruction and therefore less plant will survive.

Table 6.1 gives vulnerability values per pixel for different magnitude classes. The value is taken as 0.5 for a landslide of size M-II as it will affect only 50% of a pixel area (50 m² area) and the remaining unaffected 50% area will continue to yield. The vulnerability value equals to 1 in case of a large landslide (M-III and M-IV), which generally results in complete removal of soil cover and therefore no plant can survive. In contrast to tea, the horticulture plantations, which consist of plant nurseries and spice trees, are
less vulnerable for a landslide of magnitude M-II. In such slides spice trees are expected to withstand and losses are more from small plants and nurseries, which are difficult to extract once they are lost in landslide debris.

In this study vulnerability of plantations affected by landslide run-out was not estimated because the method used does not allow the evaluation of run-out for large spatial units due to the lack of information on the deposition area. Vulnerability of forest resources and indirect losses in production in years after a landslide occurrence were not estimated because these are not directly the sources of livelihood for the population.

6.2.3.2 Vulnerability of transport infrastructures
The assessment of the vulnerability of the railroad and the road was based on the information obtained from historical damaging events in the area. For the railroad a detailed analysis of the direct monetary losses due to landslides in the 16-year period from 1992 to 2007 was carried out. The damage data were taken from the railway slip register, which is available only for this period, and includes the type of damage such as the number of damaged rails, rake bars and sleepers, and the cost involved in the repair of the damaged structures. The vulnerability of the road components was assessed based on the damage information obtained from the Highway office. Vulnerability was estimated separately for landslides initiating on natural slopes and on cut slopes because the impact pressure of both type of failures is different due to the difference in their travel distance and the size of landslides. Because of the small size of cut slope failures, only the maximum vulnerability is assessed for each of the magnitude class so that the maximum risk can be calculated.

The vulnerability represents the ratio of the total restoration cost to the actual construction costs, where the cost is taken as US$/pixel for natural slope failures and US$/m for cut slope failures. Each pixel covers a length of 10 m. In cases where the vulnerability is assessed by comparing the monetary loss per damaged section of the infrastructure by a landslide (e.g., US$/m) with the actual construction costs, the vulnerability could theoretically be greater than 1 since the repair could cost more than constructing new infrastructure as it includes the additional cost of removing debris and also replacing damaged components. However, in this analysis the maximum value considered for the vulnerability is 1 (total loss).

Table 6.1 gives vulnerability values per pixel of the road and railroad located in the initiation area of a landslide of different magnitude classes. A small landslide (M-II) generally affects only part of the slope on which the infrastructure is located. The restoration cost here includes cost of building a
Chapter 6

retaining wall for the stabilization of the slope. The expected restoration cost for stabilizing can be 30% (vulnerability = 0.3) and 50% (vulnerability = 0.5) of the actual construction cost of a section of 10 m of a road and railroad, respectively. A slightly bigger slide can cause some damage to the structures also and therefore in addition to the cost of constructing a retaining wall the restoration cost will include replacing the damaged components and leveling of the ground. For a bigger landslide (M-III and M-IV) the restoration cost becomes equal or exceed the construction cost because big landslides are expected to cause complete damage of the infrastructure and therefore the vulnerability is taken as 1 (total loss). In contrast to the road vulnerability values are higher for the railroad for landslides of magnitude class M-II because of the higher cost of transportation of building materials along the railroad.

Table 6.2 gives vulnerability values of the road and railroad located in the run-out path of a landslide for different magnitude classes. The total restoration costs here include the costs of removing landslide debris from the (rail) road and those of replacing the damaged components. The cost of removing debris from the railroad is the fixed contract rate which was obtained from the existing cleaning contracts (US$ 5 per m³) and the cost of constructing a new railroad was determined to be US$ 110 per meter for the situation in 2007. The data were obtained from the Southern Railway office in Coonoor. The road is a national highway approximately 10 m wide including an 8 m wide asphalt cover. It contains two bitumen layers of 75 mm (lower layer) and 20 mm (upper layer) thickness. The cost of constructing the lower layer (2007 situation) was US$ 34 per m³ and for the upper layer US$ 4 per m² and the total cost of making a new road were US$ 50 per meter, which includes only the cost of making the surface of the road and not the ground work, drainage work, etc. The cost of removing debris from the road was determined from contracts to be US$ 0.7 per m³. The length of infrastructure being affected and the amount of debris being accumulated on the road and railroad depend on the size of a landslide. The historical records suggest that landslides of class M-II, M-III and M-IV affect about 10 to 30 m, 30 to 50 m and 50 to 100 m length of the infrastructures, respectively and the amount of debris accumulated varies from 100 m³ to 5,000 m³. For bigger landslides not all debris is accumulated on the (rail) road rather these landslides have longer run-out and part of the debris passes the (rail) road. For the railroad the vulnerability is set to 1 for all landslide magnitude classes because the debris are expected to cause maximum damage due to the high impact. Figure 6.4B shows the damage caused to the railroad by a landslide of class M-II. The landslide completely damaged a 20 m section of the railroad and
the restoration cost was more than the actual construction cost (vulnerability = 1) because it also included cost of removing landslide debris.

In case of the road, the historical records indicate that landslides generally do not cause major structural damage to the road and the restoration cost mainly involves the cost of removing debris and minor repairs such as repair of parapet walls, culverts, etc. even if the landslide belongs to class M-IV, as seen in Figure 6.4C, where a landslide of ~16,000 m$^3$ did not cause any structural damage to the road. However, for class M-IV the total restoration cost is more than the actual construction cost because in addition to removing debris it also includes construction of a protection wall to contain further flow of debris on the road (vulnerability = 1). For relatively smaller landslides (M-II and M-III) the vulnerability varies from 0.2 to 0.8.

Table 6.3 gives vulnerability values of the road and railroad for a landslide initiating on a cut slope. For very small landslides of less than 100 m$^3$ the damage records indicate that the components of the railroad generally are not damaged by these slides and the restoration cost in such cases only involves the cost of removing debris. For the railroad, vulnerability was calculated without taking into account the construction of bridges and the slope cutting. The railway bridges are constructed with a sufficient altitude above the channel beds so they are hardly ever damaged by such landslides. Theoretically, vulnerability can vary considerably with the decrease in landslide size (e.g., volume < 100 m$^3$) but may not vary significantly for large landslides, which often result in a total damage of the element (e.g., vulnerability=1). I have assigned one vulnerability value for each magnitude class, which was estimated from the maximum volume in that class.

6.2.3.3 Vulnerability of buildings
For vulnerability calculation the buildings were grouped into four types, based on the material strength of building structure: Type-1 (tin shed, Figure 6.5A), Type-2 (brick in mud without column structure, Figure 6.5B), Type-3 (brick in cement with column structure, Figure 6.5C) and Type-4 (reinforced concrete, Figure 6.5D). The Type-1, Type-2, Type-3 and Type-4 buildings respectively constitute 2%, 80%, 16% and 2% of the total buildings. The vulnerability of buildings was subjectively assessed based on limited historic incidents. The vulnerability was estimated as the ratio of monetary loss to the total value of the building and its contents. The monetary loss includes the cost of repair of damaged parts of the building and its contents, strengthening of the foundation and the cost of removing debris from the building.
Figure 6.4 Landslide damage information used for the vulnerability assessment. A: tea plants, B: railroad, C: road, D: Type-2 building, E: Type-3 building, F and G: Type-4 building, H: Type-2 building partly damaged by a landslide and I: Type-4 building partly damaged by a landslide.
Table 6.1 Estimated vulnerability of elements at risk located in landslide initiation areas.

<table>
<thead>
<tr>
<th>Element at Risk</th>
<th>Vulnerability due to a landslide of magnitude class</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M-II</td>
</tr>
<tr>
<td></td>
<td>min</td>
</tr>
<tr>
<td>Tea/coffee plantation</td>
<td>0.5</td>
</tr>
<tr>
<td>Horticulture plantation</td>
<td>0.2</td>
</tr>
<tr>
<td>Railroad</td>
<td>0.5</td>
</tr>
<tr>
<td>Road</td>
<td>0.3</td>
</tr>
<tr>
<td>Building types</td>
<td></td>
</tr>
<tr>
<td>Type-1</td>
<td>0.3</td>
</tr>
<tr>
<td>Type-2</td>
<td>0.1</td>
</tr>
<tr>
<td>Type-3</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 6.2 Estimated vulnerability of elements at risk located within run-out paths of a natural slope failure.

<table>
<thead>
<tr>
<th>Element at Risk</th>
<th>Vulnerability due to a landslide of magnitude class</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M-II</td>
</tr>
<tr>
<td></td>
<td>min</td>
</tr>
<tr>
<td>Railroad</td>
<td>1</td>
</tr>
<tr>
<td>Road</td>
<td>0.2</td>
</tr>
<tr>
<td>Building types</td>
<td></td>
</tr>
<tr>
<td>Type-1</td>
<td>1</td>
</tr>
<tr>
<td>Type-2</td>
<td>0.2</td>
</tr>
<tr>
<td>Type-3</td>
<td>0.1</td>
</tr>
<tr>
<td>Type-4</td>
<td>0</td>
</tr>
</tbody>
</table>

For a building located in the initiation area of a landslide on natural slope the monetary loss mostly involves cost of strengthening the foundation of the building if part of the slope underneath the building fails. In case if the entire slope fails or the building collapses then the building has to be reconstructed and therefore the monetary loss is equal to its value. The Type-1 buildings are relatively more vulnerable because these are individually small, have a weak foundation and are often located adjacent to the slope face and therefore they are subjected to total damage even if part of the slope fails. Figure 6.4E shows a Type-1 building whose foundation was partly removed by a small slide. Since the total value of such buildings is less therefore the ratio of the cost of treatment of its foundation to the value of the building is always high (vulnerability ≥0.5). The Type-2 and Type-3 buildings have relatively better material strength but since the cost of slope or foundation treatment works are high therefore even for M-II slides the treatment cost can range from 10% to 80% of their total value. This value can increase to 100% (vulnerability =1) if the landslide is bigger than M-III or if complete
reconstruction of the building is required. An example is shown in Figure 6.4D and Figure 6.4F where a M-II and M-III landslide requires treatment in order to protect the foundation of a Type-2 and Type-3 building, respectively. Among all building types the Type-4 buildings have highest asset values and have the strongest foundation and since they are generally not located on steep slopes they are less likely to be affected by small slides (M-II class). Even in case of being affected by a small slope failure the monetary loss will be much less than their actual asset value. Based on the above incidents, different vulnerability values were assigned to the four building types located in the initiation area of a landslide of a given magnitude class (Table 6.1). The vulnerability value varies from 0 (M-II slide and building Type-4) to 1 (slides bigger than M-III and for all building types).

Table 6.3 Estimated vulnerability of elements at risk affected by a landslide from cut slopes.

<table>
<thead>
<tr>
<th>Element at Risk</th>
<th>Vulnerability due to a landslide of magnitude class</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M-I max</td>
</tr>
<tr>
<td><strong>Infrastructure</strong></td>
<td></td>
</tr>
<tr>
<td>Railroad</td>
<td>0.5</td>
</tr>
<tr>
<td>Road</td>
<td>0.2</td>
</tr>
<tr>
<td><strong>Moving vehicle</strong></td>
<td></td>
</tr>
<tr>
<td>Bus</td>
<td>0.01</td>
</tr>
<tr>
<td>Lorry</td>
<td>0.01</td>
</tr>
<tr>
<td>Car</td>
<td>0.1</td>
</tr>
<tr>
<td>Motorbike</td>
<td>0.5</td>
</tr>
<tr>
<td>Train</td>
<td>1</td>
</tr>
<tr>
<td><strong>Person in a moving vehicle (probability of death)</strong></td>
<td></td>
</tr>
<tr>
<td>Bus</td>
<td>0.001</td>
</tr>
<tr>
<td>Lorry</td>
<td>0.001</td>
</tr>
<tr>
<td>Car</td>
<td>0.01</td>
</tr>
<tr>
<td>Motorbike</td>
<td>0.5</td>
</tr>
<tr>
<td>Train</td>
<td>0.5</td>
</tr>
</tbody>
</table>

For buildings located within the run-out path of a landslide initiating on natural slope vulnerability was assessed based on historic incidents. Among these was a debris flowslide of class M-IV at Marapallam which completely destroyed the entire settlement. In 2009, a debris flowslide of class M-IV damaged a Type-4 building (Figure 6.4G) located on its run-out path (vulnerability =0.8). In 2006, a debris flowslide of class M-III partly damaged one Type-3 building such that the monetary loss, including removing of debris was 70% of its value (vulnerability =0.7). In the same year a debris flowslide of class M-II completely destroyed a Type-1 building (police check post) injuring three policemen (vulnerability =1). In 2009, a landslide of class M-II damaged a Type-2 building (vulnerability =0.8) located below the slide.
Landslide Risk assessment

killing five people (Figure 6.4H) and in another incident a landslide of class M-III partially damaged a Type-4 building (vulnerability =0.1) located in the run-out path (Figure 6.4I).

Based on the assessed values, different vulnerability values to each building type for a landslide of a given magnitude class were assigned as shown in Table 6.2.

![Figure 6.5 Building types in the study area. A: tin shed, B: brick in mud without column structure, C: brick in cement with column structure and D: reinforced concrete.](image)

### 6.2.3.4 Population vulnerability

Even though there have been a number of fatal landslides, the assessment of population vulnerability is prone to large uncertainty. It depends on many factors, including reflex and consciousness of the person at the time of impact, his/her physical condition, age and his/her perception about risk.
Some of the known incidents of landslide casualties include a landslide of class M-IV in Marapallam which completely damaged all houses and killed all occupants. In 2006, a landslide of class M-II completely destroyed a Type-1 building (police check post) but these policemen escaped with major injuries (vulnerability of Type-1 building=1 and vulnerability of people in that building=0.4). In 2009 a slide of M-II damaged a house shown in Figure 6.4H and killed five out of six family members (vulnerability of Type-2 building=0.8 and vulnerability of people in that building=0.8). In another incident in 2009 a debris flow of class M-III that damaged the house shown in Figure 6.4I also inundated another Type-3 house located on its run-out path killing the woman present in the house.

Based on the above incidents, vulnerability values for persons occupying different types of buildings affected by a landslide of a given magnitude class initiating from a natural slope were assigned (Table 6.4). The vulnerability represents the probability of loosing life given the landslide impact on the building. For value 1 death is almost certain and less than 0.5 indicates a high chance of survival. The chances of survival are relatively more if a person is occupying a Type-4 building because of the higher building strength. In this study vulnerability to people outside was not considered.

Table 6.4 Vulnerability of people in buildings impacted by a landslide.

<table>
<thead>
<tr>
<th>Building types</th>
<th>M-II</th>
<th>M-III</th>
<th>M-IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type-1</td>
<td>0.4</td>
<td>0.8</td>
<td>1</td>
</tr>
<tr>
<td>Type-2</td>
<td>0.2</td>
<td>0.6</td>
<td>0.8</td>
</tr>
<tr>
<td>Type-3</td>
<td>0.1</td>
<td>0.4</td>
<td>0.6</td>
</tr>
<tr>
<td>Type-4</td>
<td>0</td>
<td>0</td>
<td>0.2</td>
</tr>
</tbody>
</table>

6.2.3.5 Vulnerability of a moving vehicle

The assessment of vulnerability of different types of moving vehicles (train, bus, lorry, car and motorbike) was carried out based on historic incidents where landslides from cut slopes hit moving vehicles. In one incident, near the Katteri farm, landslide debris from a landslide of magnitude class M-II pushed two moving cars across the road causing damage. The repair cost of each car was approximately as 50% of its value (vulnerability =0.5). In 2006 a moving lorry was hit by a landslide of magnitude class M-III and the expected repair cost was more than 50% of the value of the lorry. The vulnerability of a moving vehicle depends on the speed and type of vehicle, the volume of landslide debris and the type of the transportation line. Theoretically a small, light weight vehicle such as a motorbike is more...
vulnerable than a big, heavy vehicle such as a bus or a truck. A train is vulnerable to a landslide because it takes some time to stop a moving train if the track or the train is hit by a landslide and derailment on a steep hill will certainly result in damage to the train. Vulnerability for different types of moving vehicles for landslides of different magnitude classes are given in Table 6.3. Landslides of magnitude class M-I and M-II are relatively small and expected to cause less damage (monetary loss) to big vehicles (vulnerability ~0.01 - 0.1) but can be disastrous for motorbikes (vulnerability ~0.5 - 0.8). In reality moving vehicles are also vulnerable to landslides initiating on natural slopes, however, in the study area most of the known incidents are due to landslides initiating on cut slopes.

6.2.3.6 Vulnerability of a person in a moving vehicle
The vulnerability of a commuter to a landslide depends on the type and size of the landslide, the speed and type of the vehicle, and whether the person is in the open or inside a vehicle (Wilson et al., 2005). It also depends on whether the debris directly hits the vehicle from the top or from the side. On 14 November 2006, a driver was killed and his associate was injured when a landslide of magnitude M-III from a cut slope hit a moving truck (vulnerability =0.8). In this analysis a single vulnerability value was taken for each magnitude class. Each magnitude class contains landslides with a range of volumes, for example M-I contains landslides ranging from 2 to 100 m$^3$ and therefore their vulnerability also varies according to the volume of the landslide. The vulnerability is usually higher for landslides with larger volumes. For this analysis I have taken the maximum vulnerability for each magnitude class. The value was related to the maximum volume of the landslides in each magnitude class.

The vulnerability of people when a vehicle is hit by landslides from cut slopes of different magnitude classes is given in Table 6.3. The vulnerability represents the probability of loosing life given the landslide impact on the moving vehicle. Landslides of magnitude class M-I and M-II are relatively small and people travelling in big vehicles are less vulnerable than those travelling on motorbike (vulnerability ~0.5 - 1).

6.2.4 Estimation of direct risk
Direct risk was estimated for elements that can be directly affected by landslides. Physical infrastructural components (components of the railroad and road) are directly affected by landslides initiating from both cut slopes and natural slopes. For moving vehicles (trains, buses, trucks, cars and motorbikes), and commuters (road and train users) risk was estimated only for landslides from cut slopes, whereas for plantations, buildings and
population risk was estimated only for landslides from natural slopes. For the latter case, direct risk was estimated for elements at risk located in landslide initiation areas, and within landslide run-out zones separately.

6.2.4.1 Direct risk to properties

Direct risk to properties (i.e., infrastructure components) for landslides from cut slopes was estimated for a given return period using the expression adapted from Fell et al. (2005):

\[
RD_{p:\text{cut}} = \sum_{m=1}^{m=n} (H_{\text{cut};m} \times P_{Lm;p} \times P_T:p \times V_{p:Lm} \times A_p)
\]

where, \(RD_{p:\text{cut}}\) is the direct risk to properties (US$), \(H_{\text{cut};m}\) is the hazard due to landslides of magnitude class ‘\(m\)’ (nr per km), \(P_{Lm;p}\) is the probability of a landslide with magnitude ‘\(m\)’ reaching the infrastructure (0-1), \(P_T:p\) is the temporal probability of the infrastructural components to be exposed to a landslide of magnitude ‘\(m\)’ (0-1), \(V_{p:Lm}\) is the vulnerability of the property i.e., infrastructural components caused due to the occurrence of a landslide of magnitude ‘\(m\)’ (0-1), and \(A_p\) is the quantification (monetary value) of the property (US$). The specific risk is calculated per standard length of the road or railroad (e.g., per kilometer). The specific risk for different landslide magnitudes for each return period is integrated to generate the combined specific risk for a particular infrastructure element.

The direct combined risk to components of the road (the asphalt layers, culverts, side drains, etc.), \(RD_{rd:\text{cut}}\) and the railroad (gravel bed, rails, rake bars and sleepers), \(RD_{rl:\text{cut}}\) was estimated using Eq. (6.1). Other components of a railroad such as poles, cables, etc. are not present because the train is powered by a steam engine. The value of \(P_T:p\) was taken as 1 as these elements are stationary objects. The value of \(P_{Lm;p}\) was also taken as 1 because the infrastructure components are located below the cut slopes and landslides from these cut slope invariably reach them. The vulnerability value for infrastructural component \((V_{p:Lm})\) was taken from Table 6.3. Values for \(A_p\) were taken as US$ 110 and US$ 50 per meter length for railroad and road, respectively. Direct risk was presented for different sections along the (rail) road as annualised losses. When calculating the specific risk, it was assumed that all landslides of a given magnitude class in a given return period have the same volume which is used in the estimation of the vulnerability. Since the vulnerability was estimated from the maximum volume in a given magnitude class, the calculated risk gives the maximum loss.
Direct risk to properties located in the initiation areas of potential landslides on natural slopes was estimated for a given return period using the expression adapted from Fell et al. (2005):

\[
RD_{p:Li} = \sum_{m=1}^{m=n} \left( H_{nat:m} \times V_{p;Lm} \times A_p \right) \tag{6.2}
\]

where, \( RD_{p:Li} \) is the direct risk to the property located in a landslide initiation area (US$), \( H_{nat:m} \) is the probability of occurrence of a landslide of size ‘m’ (0-1), \( V_{p;Lm} \) and \( A_p \) are explained in Eq. (6.1). For each return period the specific risk was estimated considering the minimum, average and maximum landslide volumes of each magnitude class and their corresponding minimum, average and maximum vulnerability values. The specific risk for different landslide magnitudes was added for each return period to generate the combined specific risk resulting in minimum, average and maximum landslide risk estimated for four time periods.

Risk was analyzed for tea/coffee plantations, horticulture plantations, buildings, the road and the railroad using Eq. (6.2). For each property the value for \( V_{p;Lm} \) was taken from Table 6.1. Values for \( A_p \) were taken as US$ 37 and US$ 36 per pixel (100 m²) for tea/coffee and horticulture plantations, US$ 1,100 and US$ 500 per pixel length (10 m) for railroad and road. Building costs were determined for each building separately varying from US$ 300 (Type-1 building: a police check post) to US$ 870,000 (Type-4 building: a tea factory). The elements at risk maps and the landslide susceptibility map were combined in GIS and for each pixel the combined specific risk to tea/coffee plantations (\( RD_{tea:Li} \)), horticulture plantations (\( RD_{hort:Li} \)), buildings (\( RD_{bld:Li} \)), road (\( RD_{rd:Li} \)) and railroad (\( RD_{rl:Li} \)) were estimated using Eq. (6.2). The results were presented as annualized losses and displayed as risk curves.

The method based on Eq. (6.2) results in numerous specific risk scenarios that are difficult to present in a single map for the benefit of stake holders. For each element at risk there are about 12 risk maps obtained considering four return periods and the minimum, average and maximum landslide magnitudes. These maps provide information important for quantitative cost-benefit analysis and selecting risk tolerance criteria. But in order to facilitate land use planning, which is often carried out for a certain time period, it is important also to depict losses as expected within a given time period. Therefore, besides calculating landslide risk as annualized losses, risk can also be calculated for a time period of \( N \) years using Eq. (6.2). Recurrence time was translated into probability by using the following equation:
Chapter 6

\[ P = 1 - \left(1 - \frac{1}{T}\right)^N \]  

(6.3)

where, \( P \) is the probability of occurrence of the event in \( N \) years and \( T \) is the return period of the event. Although numerous scenarios are possible by taking different values of \( N \) in Eq. (6.3), however, for this analysis risk to properties was calculated only for a time period of 10 years. A short time period is selected here because the hazard is estimated for events having relatively low return periods.

Direct risk from landslides on natural slopes located above properties for a given return period was estimated using the expression adapted from AGS (2000):

\[ RD_{p:LR} = \sum_{m=s}^{m=n} (H_{nat:m} \times P_{Lm:p} \times V_{p:Lm} \times A_p) \]  

(6.4)

where, \( RD_{p:LR} \) is the direct risk to the property located within the run-out path of a landslide (US$), \( P_{Lm:p} \) is the probability of a landslide with size \( 'm' \) reaching the element at risk from the upslope areas (0-1), and \( V_{p:Lm} \) is the vulnerability of the element at risk due to a landslide run-out caused by a landslide of size \( 'm' \) (0-1). \( H_{nat:m} \) and \( A_p \) are the components used in Eq. (6.2). The specific risk for different landslide magnitudes is added for each return period to generate the combined specific risk for the particular element.

For each individual building and section of the road and railroad the possibility of a potential landslide of a given volume (i.e., minimum, average and maximum volumes of each magnitude class) reaching the element at risk was assessed based on the relation shown in Figure 5.14 and the method described in Section 6.2.2. The various run-out distances (with their minimum, average and maximum ranges) for the three different magnitude classes were projected upslope and checked whether within these distances areas were encountered with low, moderate and high landslide initiation hazard. If the properties are located within the run-out distance, the value of \( P_{Lm:p} \) is taken as 1 and for landslides whose run-out do not reach the elements, the value is 0. The values for \( V_{p:Lm} \) for the buildings, road and railroad are taken from Table 6.2. Using Eq. (6.4) the combined specific risks to buildings (\( RD_{bld:LR} \)), railroad (\( RD_{r:rLr} \)) and road (\( RD_{rd:LR} \)) were estimated.

6.2.4.2 Direct risk to moving vehicles

Direct risk to a moving vehicle, i.e., a vehicle being hit by a landslide, depends on the probability \( (P_{r:veh}) \) of the vehicle being at the location of a
Landslide Risk assessment

landslide when it occurs. This probability \( P_{T;veh} \) was used to calculate the specific risk to a moving vehicle for a given return period using the following three expressions (adapted from AGS, 2000):

\[
RD_{sv} = P(V_m) \times V_{veh;m} \times A_{veh} \tag{6.5}
\]

\[
P(V_m) = 1 - (1 - P_{T;veh})^{Nr} \tag{6.6}
\]

\[
P_{T;veh} = (ADT \times L)/(24 \times 1000 \times S_{veh}) \tag{6.7}
\]

where, \( RD_{sv} \) is the direct specific risk to vehicles (US$), \( P(V_m) \) is the probability of one or more vehicles being hit by a landslide initiating from a cut slope with a magnitude ‘\( m \)’ (0-1), \( V_{veh;m} \) is the vulnerability of the vehicle for a landslide of magnitude ‘\( m \)’ (0-1), \( A_{veh} \) is the cost of the vehicle (US$), \( P_{T;veh} \) is the probability of a vehicle occupying the portion of the road onto which the landslide hits with a given magnitude ‘\( m \)’ (0-1), \( N_r \) is the number of landslides of magnitude ‘\( m \)’ initiating from cut slopes, \( ADT \) is the average daily traffic (vehicles per day), \( L \) is the average length of the vehicle (m) and \( S_{veh} \) is the speed of the vehicle (km/hr).

The parameters required for Eqs. (6.5 - 6.7) were obtained from historical incidents and field calculations. Though the speed limit on the road is 40 km/hr, the average speed was measured as 26 km/hr, based on the journey time that most of the vehicles took to cover the journey between the Kallar farm and Coonoor. The average speed of the train was measured as 11 km/hr. The ADT values were taken from a toll gate register and the train time table. The ADT for buses, lorries, cars and motorbikes was obtained as 137, 309, 554 and 90 vehicles per day, and for the train it was two per day. The average length (\( L \)) of a bus, lorry, car, motorbike and train was measured as 12, 8, 5, 2 and 55 m, respectively. Using Eqs. (6.5 - 6.7), specific risk to buses (\( RD_{bus} \)), lorries (\( RD_{lor} \)), cars (\( RD_{sc} \)), motorbikes (\( RD_{smb} \)) and trains (\( RD_{st} \)) was calculated for each hazard scenario. To calculate risk to a single vehicle the value of \( ADT \) in Eq. (6.7) is set to 1. Different examples of calculation of landslide risk along roads are given in Fell et al. (2005).

Since the vulnerability was estimated from the maximum volume in a given magnitude class, the calculated risk gives the maximum loss.

6.2.4.3 Direct risk to loss of life

Direct risk to loss of life of commuters

The risk of life or the annual probability of a person losing his/her life while travelling in a vehicle depends on the probability of the vehicle being hit by a
landslide \( P(V_m) \) and the probability of death of the person (vulnerability) given the landslide impact on the vehicle.

The specific risk to commuters for a given return period was estimated using the following expression (adapted from AGS, 2000):

\[
RD_c = P(V_m) \times V_{c;m}
\]

(6.8)

where, \( RD_c \) is the annual probability of death (0-1), \( V_{c;m} \) is the vulnerability of the individual commuter (probability of death) given the landslide with magnitude ‘\( m \)’ from a cut slope impact on the vehicle (0-1). The parameter \( P(V_m) \) is estimated using Eqs. (6.6 - 6.7). For a single vehicle being hit by a landslide, the value of \( ADT \) in Eq. (6.7) is set to 1.

Using Eq. (6.8) and setting \( ADT \) to 1,, the specific risk in terms of annual probability of the person most at risk losing his/her life by travelling in a bus (\( RD_{cb} \)), lorry (\( RD_{cl} \)), car (\( RD_{cc} \)), motorbike (\( RD_{cmb} \)) and train (\( RD_{ct} \)) was calculated for each hazard scenario.

**Direct risk to population**

Direct specific risk to persons occupying the building affected by a landslide from an upslope area was estimated using the expression adapted from AGS (2000):

\[
RD_{pop} = H_{nat;m} \times P_{Lm:bt} \times P_{pop:bt} \times V_{pop:Lmbt}
\]

(6.9)

where, \( RD_{pop} \) is the annual probability that a person will be killed (0-1), \( H_{nat;m} \) is the annual probability of occurrence of a landslide of size ‘\( m \)’ (0-1), \( P_{Lm:bt} \) is the probability of a landslide with size ‘\( m \)’ reaching the building of type ‘\( t \)’ from the upslope areas (0-1), \( P_{pop:bt} \) is the probability that the person is present in the building of type ‘\( t \)’ affected by the hazard at the time of its occurrence (0-1), \( V_{pop:Lmbt} \) is the vulnerability of the person given a landslide of size ‘\( m \)’ impacting the building of type ‘\( t \)’ (0-1).

For people occupying the buildings, \( P_{pop:bt} \) was calculated based on the proportion of time in a year the persons occupy the building. The occupancy rate of persons depends on the use of the building. For persons occupying a house almost continuously (e.g., old persons, housewives, etc.), the value of \( P_{pop:bt} \) was taken as 1 and for working people in offices and tea factories, and school children in a school, it was calculated based on 8 hours and 5 days a week as 0.23. For persons occupying the building during the night for 12
hours the value of $P_{\text{pop, bt}}$ was calculated as 0.5. The vulnerability of persons occupying buildings of different types ($V_{\text{pop, Lmbt}}$) is taken from Table 6.4.

### 6.2.5 Estimation of indirect risk

The indirect risk estimation requires two basic parameters: the hazard scenario that defines the blockage time of the transportation lines, and a socio-economic analysis of the study area to determine the most important activities in the area and their consequences to the society if disrupted.

Every month on average 200,000 tourists visit the Nilgiri area (Venugopal, 2004). The area is connected with Mettupalayam by a National Highway road (NH-67) and a railway. The NH-67 provides the shortest driving route between Coonoor and Mettupalayam. The alternate road via Kotagiri takes more time (about double) to reach Mettupalayam than by NH-67. The railroad is the other mode of travel but it also takes more time to reach Mettupalayam than travelling by NH-67 and it is mostly used by tourists. Tourists generally undertake the train journey once in their stay period either for coming to Coonoor or going back to Mettupalayam.

Besides tourism the Nilgiri is also known for several other businesses and services such as institutions, schools, tea production, etc. Every day a large number of people travel in and out of the Nilgiri for the purpose of work. The travellers from Mettupalayam and Coimbatore area usually take NH-67 for their journey. Also along NH-67 numerous shops and other businesses are located, which totally depend on travellers for their livelihood. Therefore, a blockage of NH-67 has higher indirect consequences to the society in general and to the local residents in particular, than a blockage of the railway.

I analyzed four types of indirect losses resulting from the temporal blockage of the transportation lines from landslides on cut slopes: additional fuel consumption; additional travel cost; loss of income to the local business; and loss of revenue to the railway.

At first step the alternate driving routes are identified in case of the blockage of the main line. The traffic such as type of vehicles, intensity, tourist and local vehicles were estimated from data supplied from the revenue office at Coonoor and tollgate register of 2007. Estimates for revenue loss to the railway and average numbers of passengers were obtained from the railway office at Coonoor. The types of business and their losses were obtained through participatory mapping i.e., the local residents were interviewed and questions were asked pertaining to their livelihood, type of business, monthly
income, physical status, family details, number of dependents and any information regarding landslide damage and loss.

In the event of a blockage of the NH-67 road, a certain amount of travellers decide to take the alternate road via Kotagiri to reach Coonoor. Due to the availability of an alternate road, tourists and local people usually undertake their journey irrespective of the extra cost of the travel. For example in November 2006 the NH-67 was closed for a few days due to landslides and during the period the entire traffic was diverted via Kotagiri. The incident was highlighted in the newspaper and described as “Kotagiri-Mettupalayam road under strain” (Hindu, 2006). The road from Mettupalayam to Coonoor via Kotagiri covers an extra distance of 32 km. To calculate loss due to the alternative driving route, it is assumed that tourist vehicles will cover this distance only once a day, while local Nilgiri vehicles will cover at least twice a day (i.e., onward and return). The mileage (fuel consumption per liter) also varies according to vehicle type, and for analysis the value was taken as 5, 4, 10 and 30 km/l for a bus, lorry, car and motorbike, respectively. The values were based on the official mileage rate fixed by the local transport office for the year 2007. The fuel cost was established as US$ 0.8 per litre, which is the average value of diesel and petrol cost in the Nilgiri area in 2007. Indirect combined risk for additional fuel consumption for a given return period was calculated using the following expression:

\[
R_{IFC} = \sum_{m=1}^{m=n} \left[ \frac{(ARL \times ADT \times FC \times TBT_m)}{MV} \right]
\]  

(6.10)

where, \( R_{IFC} \) is the indirect combined risk (monetary loss) due to additional fuel consumption by vehicles (US$), \( ARL \) is the alternate road length (km), \( ADT \) is the average daily traffic (vehicles per day), \( FC \) is the fuel cost (US$/l), \( TBT_m \) is the traffic blockage time due to landslides with magnitude ‘m’ (day) and \( MV \) is the mileage of the vehicle (km/l).

Traffic blockage time was obtained by dividing the total volume of debris (m³) on the road by the average debris clearance rate (m³/day). The total volume of landslide debris was calculated from the hazard, which provides the number of landslides of magnitude classes M-I, M-II and M-III from cut slopes along the road. The number of landslides was multiplied by the median volume of each magnitude class to obtain the total volume of debris. The median value for each magnitude class was obtained from the landslide inventory, which is 20, 200, 1,700 m³ for landslides of M-I, M-II and M-III class, respectively. The average clearance rate along the road is 1,100 m³ of
debris per day. This value was estimated from the actual clearance rate, which is 20 lorries of debris per hour with 5 m³ of material per lorry.

Every day a large number of people travel in and out of Coonoor for work or for other purposes. In the event of road blockage they have to pay comparatively higher cost for tickets due to the longer travel distance, which is about US$ 0.13 per journey. Every day on an average 120 local buses pass via Coonoor with an average capacity of 50 passengers. To calculate the additional cost of travel, I assumed that each bus carries at least 50 passengers who have to pay additionally US$ 0.13 per journey. It may be possible that people may travel by other vehicles such as taxi, but in this area busses remain the main mode of travel and thus for analysis the other types of vehicles were not considered. Indirect combined risk for additional travel cost for a given return period was calculated using the following expression:

\[ RI_{TC} = \sum_{m=1}^{m=n} ADC \times CT \times TBT_m \]  \hspace{1cm} (6.11)

where, \( RI_{TC} \) is the indirect combined risk (monetary loss) due to additional travel cost (US$), \( ADC \) is the average commuters per day, \( CT \) is the cost of ticket (US$) and \( TBT_m \) is the traffic blockage time due to landslides with magnitude ‘m’ (days).

Another adverse effect of the road blockage is on local business, which depends on road travellers on NH-67. These include shops, restaurants and hotels. In the Katteri area there are 11 business units and around Burliyar there are 35 units. The average loss of each business was obtained by participatory survey. In Katteri, the average loss to restaurants, shops and hotels is approximately 75, 50 and 30%, respectively and around Burliyar it is 100%. The difference in the percentage loss is due to the location of the business. Katteri is located near Coonoor and is accessible by other local roads from west and north, but Burliyar is in the middle of the study section and hence it is totally cut-off during the blockage. Indirect combined risk for business for a given return period was calculated using the following expression:

\[ RI_B = \sum_{m=1}^{m=n} NBT \times ADI \times P_{loss} \times TBT_m \]  \hspace{1cm} (6.12)

where, \( RI_B \) is the indirect combined risk (monetary loss) to business (US$), \( NBT \) is the number of businesses, \( ADI \) is the average daily income from the
business (US$/day), $P_{loss}$ is the probability of loss in income (0-1) and $TBT_m$ is the traffic blockage time due to landslides with magnitude $m$ (days).

Another indirect loss is due to the blockage of railroad. The closure of rail traffic does not directly affect people economically but results in a revenue loss to the railway. It also results in an emotional loss to tourists who purposely visit the area for a train ride. The train is known as a ‘Nilgiri toy train’ and runs between Coonoor and Mettupalayam twice a day. It is a small passenger train with a total sitting capacity of 200 people and also it is one of the major tourist attractions in the area (Figure 6.6). Indirect combined risk to the railway department in a given return period was calculated using the following expression:

\[
R_I_R = \sum_{m=1}^{m=n} DIL \times TBT_m
\]

(6.13)

where, $R_I_R$ is the indirect combined risk (monetary loss) to the railway department (US$), $DIL$ is the daily income loss (US$/day) and $TBT_m$ is the traffic blockage time due to landslides with magnitude $m$ (days).

The daily income includes revenue generated from the sale of tickets, which is on average US$ 280/day. The traffic blockage time due to landslides was estimated from historical damage data obtained from the railway office. The data provided the total blockage time in different years (i.e., days when the railroad was closed for the traffic) and the amount of debris that were cleared from the railroad and the repair works that were carried out. The blockage time was found to vary from four to 134 days depending on the volume of debris and type of repair works needed for the restoration of the railroad. A scatter plot was generated between the total volumes of debris (in m$^3$) on the railroad and total blockage time (days) in the period 1992 to 2007. The relation has a power law distribution with power law exponent as 0.62 and constant as 0.31. The coefficient of correlation was obtained as 0.65. This relation was used to calculate the expected traffic blockage time due to landslides with magnitude $m$ with a given return period. The traffic blockage time estimated to vary from 16 to 175 days depending on the total volume of material on the railroad.
6.2.6 Estimation of total risk

The total landslide risk is the summation of all the specific risks related to landslides in an area including the indirect risks. It is obtained when the hazard for all landslide types and magnitudes is multiplied with the expected losses for all different types of elements at risk (van Westen et al., 2006).

The total landslide risk of monetary loss in the study area was calculated by adding the total maximum risk resulting from landslides initiating on cut slopes, including both direct and indirect losses, and the total maximum risk resulting from landslides initiating on natural slopes of a given return period. The output was plotted as a risk curve, containing the relation between hazard with different annual probabilities and the corresponding total losses. The area under the curve gives the total annualized maximum loss in the study area.

6.3 Results

6.3.1 Direct risk

6.3.1.1 Risk to infrastructures, plantations and buildings

Table 6.5 and Table 6.6 give an example of the specific loss per kilometer of the railroad and the road property from landslides on cut slopes of a 50-year return period. The combined specific loss to the railroad \(RD_{R(l)}\) in \(T_3\), \(T_5\), \(T_{15}\), \(T_{25}\) and \(T_{50}\) year return period, obtained using Eq. (6.1), is estimated to be about US$ 56,100; US$ 201,700; US$ 337,300; US$ 393,700 and US$
472,700, respectively. The average historical annual loss of US$ 83,000 was obtained from the past damage record for the period 1992 to 2007, which also includes other costs such as those from the daily maintenance of the track. The combined specific loss to the road ($RD_{cut}$) in $T_3$, $T_5$, $T_{15}$, $T_{25}$ and $T_{50}$ year return period is estimated as about US$ 3,900; US$ 22,500; US$ 44,400; US$ 53,500 and US$ 66,200, respectively.

**Table 6.5** Direct specific risk per kilometer of the railroad.

<table>
<thead>
<tr>
<th>Kilometer mark</th>
<th>Loss (US$ for $T_{50}$ year return period)</th>
<th>H-I</th>
<th>H-II</th>
<th>H-III</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td></td>
<td>4,532</td>
<td>36,956</td>
<td>9,297</td>
<td>50,785</td>
</tr>
<tr>
<td>11</td>
<td></td>
<td>5,549</td>
<td>45,247</td>
<td>11,383</td>
<td>62,179</td>
</tr>
<tr>
<td>12</td>
<td></td>
<td>4,918</td>
<td>40,105</td>
<td>10,089</td>
<td>55,112</td>
</tr>
<tr>
<td>13</td>
<td></td>
<td>3,906</td>
<td>31,849</td>
<td>8,012</td>
<td>43,767</td>
</tr>
<tr>
<td>14</td>
<td></td>
<td>2,610</td>
<td>21,285</td>
<td>5,355</td>
<td>29,250</td>
</tr>
<tr>
<td>15</td>
<td></td>
<td>2,621</td>
<td>21,373</td>
<td>5,377</td>
<td>29,371</td>
</tr>
<tr>
<td>16</td>
<td></td>
<td>2,280</td>
<td>18,592</td>
<td>4,677</td>
<td>25,549</td>
</tr>
<tr>
<td>17</td>
<td></td>
<td>2,089</td>
<td>17,035</td>
<td>4,286</td>
<td>23,410</td>
</tr>
<tr>
<td>18</td>
<td></td>
<td>1,823</td>
<td>14,867</td>
<td>3,740</td>
<td>20,430</td>
</tr>
<tr>
<td>19</td>
<td></td>
<td>1,512</td>
<td>12,330</td>
<td>3,102</td>
<td>16,944</td>
</tr>
<tr>
<td>20</td>
<td></td>
<td>1,407</td>
<td>11,473</td>
<td>2,886</td>
<td>15,766</td>
</tr>
<tr>
<td>21</td>
<td></td>
<td>1,514</td>
<td>12,348</td>
<td>3,106</td>
<td>16,968</td>
</tr>
<tr>
<td>22</td>
<td></td>
<td>1,847</td>
<td>15,059</td>
<td>3,788</td>
<td>20,694</td>
</tr>
<tr>
<td>23</td>
<td></td>
<td>1,493</td>
<td>12,173</td>
<td>3,062</td>
<td>16,728</td>
</tr>
<tr>
<td>24</td>
<td></td>
<td>1,517</td>
<td>12,365</td>
<td>3,111</td>
<td>16,993</td>
</tr>
<tr>
<td>25</td>
<td></td>
<td>1,373</td>
<td>11,194</td>
<td>2,816</td>
<td>15,383</td>
</tr>
<tr>
<td>26</td>
<td></td>
<td>1,193</td>
<td>9,724</td>
<td>2,446</td>
<td>13,363</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>472,692</td>
</tr>
</tbody>
</table>

H-I, H-II and H-III are the hazard related to landslide of M-I, M-II and M-III, respectively.

Figure 6.7 shows the estimated risks to different properties located in the initiation areas of potential landslides, as obtained using Eq. (6.2). The estimated risk is displayed as risk curves, which are plots of combined losses (US$) versus annual probabilities of the occurrence of triggering events. Figure 6.8 shows the maximum risk curves for different types of buildings. The average annualized maximum loss is highest for Type-3 buildings, because most (30%) of these are located in high susceptible areas (Figure 6.9). Figure 6.9 shows the percentage distribution of building types in different susceptible zones. About 92% of all mapped buildings are located in low susceptible zones.
Table 6.6 Direct specific risk per kilometer of the road.

<table>
<thead>
<tr>
<th>Section</th>
<th>Loss (US$ for T50 year return period)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>H-I</td>
</tr>
<tr>
<td>S-I</td>
<td>239</td>
</tr>
<tr>
<td>S-II</td>
<td>58</td>
</tr>
</tbody>
</table>

H-I, H-II and H-III are the hazard related to landslide of M-I, M-II and M-III, respectively.

Figure 6.10 shows the average expected losses of all elements at risk (tea/coffee and horticulture plantations, railroad, road and buildings) for a time period of 10 years. About 62% of the study area has a negligible expected loss. The expected minimum, average and maximum losses are lower than US$ 10 per pixel in 10 years for 37%, 28% and 23% area, respectively. High values of minimum and maximum risks, with expected economic losses greater than US$ 50 per pixel in 10 years occupy only 0.5% and 1% area, respectively. Such areas will deserve special attention and site specific analysis in future. Areas with expected losses between US$ 8-50 per pixel are mostly located on slopes adjacent to drainages. Such areas are vulnerable to torrent streams where debris slides can result in loss of cultivated lands and buildings located close to drainages.

The analysis of run-out hazard showed that most of buildings are either located on ridge spurs or near to the ridge tops and therefore are not vulnerable to run-out from upslope landslides. Buildings located at Kallar farm, Burliyar, Pudukadu, Crumbari, Marapallam, Katteri and Glandale were considered as vulnerable to landslide run-out. Using Eq. (6.4) the combined specific risks to buildings (RD_{bld:Lr}), railroad (RD_{r:LR}) and road (RD_{rd:Lr}) were estimated for different return periods as given in Table 6.7. For different building types, the annual maximum expected losses were ranging between US$ 20 for Type-1 buildings and US$ 1,000 for Type-4 buildings. The combined total annual losses for properties (buildings, railroad and road) were ranging between US$ 2,000 and US$ 25,000.

6.3.1.2 Risk to moving vehicles

Table 6.8 gives an example of the specific loss to a bus, lorry, car, motorbike and train due to landslides with a 50-year return period, obtained using Eqs. (6.5 – 6.7). The sum of the combined losses to moving vehicles i.e., bus (RD_{sb}), lorry (RD_{sl}), car (RD_{sc}), motorbike (RD_{smb}) and train (RD_{st}) at any given time in T3, T5, T15, T25 and T50 year return period is less than US$ 500. The total loss, considering the average daily traffic, varies from less than two US$ (motorbikes in T3 year return period) to US$ 3,200 (cars in T50 year return period). The combined loss for all vehicles on the road, from T3 to T50 year return period, varies from US$ 300 to US$ 4,000.
Figure 6.7 Specific risk to landslide initiation displayed as risk curves. A: Tea/coffee plantations; B: Horticulture plantations; C: Railroad; D: Road and E: Buildings.
Figure 6.8 Specific risk to different building types displayed as risk curves.

Figure 6.9 Percentage distribution of building types in different susceptible zones.
Figure 6.10 Expected monetary losses due to landslide initiations in US$ per pixel over a 10 year period. A: shows distribution of the average loss in the study area. B and C: show minimum and maximum loss, respectively around Katteri.

Table 6.7 Landslide risk (expressed in 1,000 US$) in the study area for different return periods for both landslide initiation (I) on natural slopes and run-out (R).

<table>
<thead>
<tr>
<th>Type of elements at risk</th>
<th>Amount (US$) in different return periods</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5 years</td>
</tr>
<tr>
<td>Tea/coffee plantations (I)</td>
<td></td>
</tr>
<tr>
<td>Horticulture plantations (I)</td>
<td></td>
</tr>
<tr>
<td>Railroad (I)</td>
<td></td>
</tr>
<tr>
<td>Railroad (R)</td>
<td></td>
</tr>
<tr>
<td>Building (I)</td>
<td></td>
</tr>
<tr>
<td>Building (R)</td>
<td></td>
</tr>
<tr>
<td>Total (I)</td>
<td></td>
</tr>
<tr>
<td>Total (R)</td>
<td></td>
</tr>
<tr>
<td>Total Risk</td>
<td></td>
</tr>
</tbody>
</table>
Landslide Risk assessment

Table 6.8 Direct specific risk for vehicles and train.

<table>
<thead>
<tr>
<th>Elements at risk type</th>
<th>Loss (US$ for T50 year return period)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>H-I</td>
</tr>
<tr>
<td>Bus</td>
<td>0</td>
</tr>
<tr>
<td>Lorry</td>
<td>0</td>
</tr>
<tr>
<td>Car</td>
<td>1</td>
</tr>
<tr>
<td>Motorbike</td>
<td>0</td>
</tr>
<tr>
<td>Train</td>
<td>190</td>
</tr>
</tbody>
</table>

H-I, H-II and H-III are the hazard related to landslide of M-I, M-II and M-III, respectively.

6.3.1.3 Risk to loss of life

The analysis shows that the annual probability of the person most at risk losing his/her life by driving along the road in a hazard of T3, T5, T15, T25 and T50 year return period is $1.2 \times 10^{-7}$, $5.7 \times 10^{-7}$, $1.1 \times 10^{-6}$, $1.3 \times 10^{-6}$ and $1.7 \times 10^{-6}$ per annum, respectively. For rail users these values are $1.6 \times 10^{-5}$, $2.4 \times 10^{-5}$, $4.0 \times 10^{-5}$, $4.7 \times 10^{-5}$ and $5.6 \times 10^{-5}$ per annum, respectively. Table 6.9 gives an example of the annual probability of death of the person most at risk travelling in a bus, lorry, car, motorbike and train due to landslides of a 50-year return period.

Table 6.9 Direct specific risk of the person most at risk using vehicle and train.

<table>
<thead>
<tr>
<th>Mode of travel</th>
<th>Loss of life (annual probability for T50 year return period)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>H-I</td>
</tr>
<tr>
<td>Bus</td>
<td>$1.7 \times 10^{-9}$</td>
</tr>
<tr>
<td>Lorry</td>
<td>$1.1 \times 10^{-9}$</td>
</tr>
<tr>
<td>Car</td>
<td>$7.0 \times 10^{-9}$</td>
</tr>
<tr>
<td>Motorbike</td>
<td>$1.4 \times 10^{-7}$</td>
</tr>
<tr>
<td>Train</td>
<td>$2.1 \times 10^{-5}$</td>
</tr>
</tbody>
</table>

H-I, H-II and H-III are the hazard related to landslide of M-I, M-II and M-III, respectively.

The incidents pertaining to death of road users due to a landslide impact are not very frequent in the study area and also there is no recorded incident of a landslide hitting the train. The loss of life of people outside of vehicles was not evaluated because of lack of data and also because this does not happen frequently. The estimated annual probability of death of road and train users is also below the suggested tolerable individual risk for the existing cut slopes, which is $1 \times 10^{-4}$ per annum (AGS, 2000) in all return periods considered in the analysis. The annual risk for all road users travelling by bus and car was also estimated. It was assumed that each bus and car carries an average of 50 and 6 persons, respectively. In a 3-year return period the annual risk (loss of lives) for both bus and car travellers is estimated as 0.0001 persons per annum. In case of road vehicles and trains in which commuters are travelling are hit by landslides, the value is found to vary
from 0.006 person per annum (in $T_3$ year return period) to 0.02 person per annum (in $T_{50}$ year return period). The low value of annual risk is the result of low number of vehicles per day.

The individual risk for persons occupying the buildings was obtained using Eq. (6.9). The annual probability is lowest for a person occupying a Type-4 building (tea factory) at Glandale, which is $8.0 \times 10^{-5}$ per annum and highest for a person occupying a Type-2 building (houses) at Pudukadu and a Type-3 building (houses) at Marapallam, which is $6.1 \times 10^{-2}$ per annum. In 1993, about 50 people died in a landslide that occurred 500 m west of this house at Marapallam.

For people occupying the buildings an estimate of the annual probability of $N$ or more lives being lost was also made and plotted the result in a cumulative frequency – consequence plot (F-N plot). Figure 6.11 shows the F-N plot for minimum and maximum values within the study area. The estimated probability of one or more lives lost varies from $2.9 \times 10^{-3}$ at Glandale to $2.1 \times 10^{-1}$ per annum at Katteri. For 100 or more lives lost the estimated probability varies from $2.9 \times 10^{-3}$ at Burliyar to $6.0 \times 10^{-2}$ per annum at Pudukadu.

### 6.3.2 Indirect risk

Table 6.10 summarizes the result of the indirect specific loss for additional fuel consumption due to landslides with a 50-year return period. The combined specific loss in $T_3$, $T_5$, $T_{15}$, $T_{25}$ and $T_{50}$ year return period amounts to US$ 5,200; US$ 33,700; US$ 66,300; US$ 80,000 and US$ 99,000 to local Nilgiri vehicles, and US$ 1,100; US$ 7,400; US$ 14,500; US$ 17,500 and US$ 21,700 to tourists vehicles, respectively. The combined loss for both local and tourist vehicles, from 3 to 50 year return period, varies from US$ 6,300 to US$ 120,700.

Table 6.11 summarizes the results of the additional travel cost estimated due to landslides with a 50-year return period. The daily cost of additional tickets is around US$ 780 for 6,000 commuters estimated travelling each day in bus. Using this value, the combined specific loss in $T_3$, $T_5$, $T_{15}$, $T_{25}$ and $T_{50}$ year return period was estimated as US$ 780; US$ 5,000; US$ 9,900; US$ 12,000 and US$ 14,800, respectively.
Figure 6.11 Calculated F-N plots for people occupying the buildings in the study area.

Table 6.10 Indirect specific risk due to additional fuel consumption.

<table>
<thead>
<tr>
<th>Mode of travel</th>
<th>Loss (US$ for T50 year return period)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>H-I</td>
</tr>
<tr>
<td><strong>For local vehicles</strong></td>
<td></td>
</tr>
<tr>
<td>Buses</td>
<td>664</td>
</tr>
<tr>
<td>Lorries</td>
<td>1,515</td>
</tr>
<tr>
<td>Cars</td>
<td>614</td>
</tr>
<tr>
<td>Motorbikes</td>
<td>18</td>
</tr>
<tr>
<td><strong>For tourist vehicles</strong></td>
<td></td>
</tr>
<tr>
<td>Buses</td>
<td>125</td>
</tr>
<tr>
<td>Cars</td>
<td>458</td>
</tr>
<tr>
<td>Motorbikes</td>
<td>32</td>
</tr>
</tbody>
</table>

H-I, H-II and H-III are the hazard related to landslide of M-I, M-II and M-III, respectively.

Table 6.11 Indirect specific risk due to additional ticket cost.

<table>
<thead>
<tr>
<th>Mode of travel</th>
<th>Loss (US$ for T50 year return period)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>H-I</td>
</tr>
<tr>
<td><strong>Bus</strong></td>
<td>422</td>
</tr>
</tbody>
</table>

H-I, H-II and H-III are the hazard related to landslide of M-I, M-II and M-III, respectively.
Table 6.12 summarizes the result of loss of business income around Katteri and Burliyar area due to landslides with a 50-year return period. The combined specific loss in T₃, T₅, T₁₅, T₂₅ and T₅₀ year return period was estimated as US$ 200; US$ 1,300; US$ 2,600; US$ 3,100 and US$ 3,900, respectively for business located at Katteri and US$ 70; US$ 450; US$ 900; US$ 1,100 and US$ 1,300, respectively for business located at Burliyar.

**Table 6.12** Indirect specific risk to local business.

<table>
<thead>
<tr>
<th>Types of business</th>
<th>Loss (US$ for T₅₀ year return period)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>H-I</td>
</tr>
<tr>
<td><strong>At Katteri area</strong></td>
<td></td>
</tr>
<tr>
<td>Hotels</td>
<td>3</td>
</tr>
<tr>
<td>Shops</td>
<td>11</td>
</tr>
<tr>
<td>Wine shop</td>
<td>98</td>
</tr>
<tr>
<td><strong>At Burliyar area</strong></td>
<td></td>
</tr>
<tr>
<td>Shops</td>
<td>38</td>
</tr>
</tbody>
</table>

H-I, H-II and H-III are the hazard related to landslide of M-I, M-II and M-III, respectively.

Table 6.13 summarizes the result of the revenue loss to the railway department due to landslides with a 50-year return period. The combined specific loss in T₃, T₅, T₁₅, T₂₅ and T₅₀ year return period was estimated as US$ 23,400; US$ 58,600; US$ 80,700; US$ 88,900 and US$ 99,600, respectively.

**Table 6.13** Indirect specific risk to the railway.

<table>
<thead>
<tr>
<th>Types of business</th>
<th>Loss (US$ for T₅₀ year return period)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>H-I</td>
</tr>
<tr>
<td>Railway</td>
<td>7,848</td>
</tr>
</tbody>
</table>

H-I, H-II and H-III are the hazard related to landslide of M-I, M-II and M-III, respectively.

The estimated loss to business is very low in comparison to other direct and indirect losses. However, for families involved in business with daily income of only few US dollars even the estimated loss of few hundred US dollars is highly significant.

### 6.3.3 Total risk

The total indirect loss resulting from the traffic interruption of the road and the railroad due to landslides on cut slopes in T₃, T₅, T₁₅, T₂₅ and T₅₀ year return period is around US$ 30,840; US$ 106,560; US$ 175,100; US$ 202,700 and US$ 240,500, respectively, and the total annualized maximum indirect loss is estimated as US$ 53,000. The total direct loss resulting from
cut slope failures is around US$ 60,000; US$ 224,200; US$ 381,700; US$ 447,300 and US$ 539,000 in $T_3$, $T_5$, $T_{15}$, $T_{25}$ and $T_{50}$ year return period, respectively, and the total annualized maximum direct loss is estimated as US$ 111,000.

Thus, the total loss along the road and the railroad, including both direct and indirect losses in $T_3$, $T_5$, $T_{15}$, $T_{25}$ and $T_{50}$ year return period amounts to US$ 90,840; US$ 330,760; US$ 556,800; US$ 650,000 and US$ 779,500, respectively.

The final combined risks for the property losses due to natural slope failures are shown in Table 6.7. The total minimum and maximum loss expected to properties for the study area in 5 to 50 year return period varies from US$ 110,000 to US$ 277,000 and US$ 679,000 to US$ 1,694,000, respectively. The total annualized maximum direct loss is estimated as US$ 268,000.

Figure 6.12 displays the risk curve of the total maximum landslide risk, which is the plot of total maximum losses (US$) versus annual probabilities of the occurrence of triggering events. The total annualized maximum total loss in the study area, which is area under the curve, is estimated as US$ 432,000.

### 6.4 Discussion and conclusions

#### 6.4.1 Risk estimation along the road and railroad

The methods allowed us to estimate landslide risk quantitatively along the road and the railroad. The hazard model expressed as the number of landslides of a given magnitude class per kilometer of cut slopes was appropriate for determining both direct and indirect risk. The number provided the frequency of landslides in different return periods, which was used to calculate the amount of debris on the transportation lines. This further formed the basis for estimating the traffic blockage time and related indirect consequences, which was otherwise not possible.
The availability of damage records of the transportation lines facilitated the calculation of vulnerability for the railroad and the road. The assessment of vulnerability for loss of life of the (rail) road users was subjective but based on historic incidents. Due to the unavailability of well documented examples of vulnerability of different types of vehicles such as a bus, lorry, car or motorbike and persons travelling in them, I was not able to compare my results with established ones. Only the vulnerability range of a person travelling in a car was comparable to the vulnerability values given in Wilson et al. (2005), which are 0.01 for debris of 30 m$^3$, 0.1 for debris of 300 m$^3$ and 1 for debris of 3,000 m$^3$.

To calculate the risk to life of the (rail) road users, the assumptions was made that the death probability is calculated only for accidents caused by the direct impact of landslide debris on a moving vehicle (both vehicle and landslide are moving). It is assumed that traffic is uniformly distributed in time. The evaluation of landslide risk to vehicles is also affected by uncertainties. The analysis was performed by considering average daily traffic values (ADT). During rush hours or during the weekends the traffic is heavier (and risk is higher), whereas during the night, traffic is lighter (and risk is lower). Instead of the posted speed limit, a calculated average speed was
used in the analysis and the traffic was assumed to be constant and continuous. The unexpected stoppage of a vehicle is not considered as it is extremely difficult to model it. The analysis also did not consider which side of the road the vehicle is travelling on, although the position of a vehicle with respect to the debris slide affects the risk. In this case the asphalt road is only 8 m wide and vehicles generally move towards the valley side for better turning and visibility. Lastly, the analysis does not consider the possibility that a vehicle can run into debris that has fallen onto the road. The total road length is 24 km and information on landslide or debris fallen on the road is quickly transmitted by local people or police check posts located at Burliyar and Katteri area. In case of landslides, all traffic is diverted via Kotagiri (alternate driving route) and therefore there is less possibility of vehicles running into the landslide debris blocking the road.

Indirect risk due to traffic interruption can include risks such as social, economic and emotional, which are difficult to quantify. Quantification of other risks such as delays to the transportation of goods, disruption to non working people, loss of working hours, unsatisfied tourists due to non availability of the train service and loss of reputation from longer blockage periods were not attempted because the estimation of these effects is beyond the scope of this study.

The methods used to estimate risk along the road and railroad have several inherent uncertainties. Medium to very high uncertainty is associated with the estimation of hazard along the (rail) road as discussed in Section 5.5.1. In spite of the uncertainty, the result can be of great value in the interpretation and assessment of direct and indirect risk for specific return periods. In the vulnerability estimation, the degree of uncertainty varies with landslide magnitude and the type and characterises of the elements at risk. For elements considered in this analysis i.e., road, railroad, vehicles and commuters, the vulnerability is not sensitive to large volume i.e., M-III (> $10^3$ m$^3$) and the uncertainty is low. For M-III, the vulnerability value for all elements at risk is either 0.8 or 1 (total damage) and therefore any further increase in the volume have no major affect on the vulnerability. But for a small volume, especially M-I, the uncertainty is very high. The vulnerability for most of the elements decreases rapidly with the decrease in the landslide volume below 100 m$^3$ and becomes insignificant for extremely small landslides. The use of single vulnerability value for M-I tends to overestimate the risk particularly in case when all expected landslides are of the size less than 100 m$^3$. 
Uncertainty in the risk analysis is also from the assumption that all landslides in a given magnitude class are of the same size, which may not hold always. The assumption was used in the estimation of risk where typical loss from one landslide was multiplied by the total number of landslides per unit length.

The major source of uncertainty associated with the indirect risk is from the estimation of traffic blockage time (TBT), which is the most important parameter. TBT is highly sensitive to the amount of debris and its value changes significantly with the change in the total landslide volume. In the indirect risk analysis, loss was estimated on a daily basis and the value was then multiplied by TBT to obtain the total loss. Thus, any uncertainty in the estimation of TBT will result in high to very high uncertainty in the risk.

Although, for landslide risk assessments it is not always practical to model uncertainties but it is possible to do sensitivity analysis by considering the effects of different assumed values for the inputs (Fell et al., 2005). A sensitivity analysis of TBT and the resulted risk was carried out using different landslide volumes. When the upper limit volume of class M-I ($10^2$ m$^3$) and M-II ($10^3$ m$^3$), and the maximum recorded volume of M-III (3,200 m$^3$ for railway and 5,200 m$^3$ for road) was considered, the estimated TBT was 251 days for the railroad and 6 days for the road and total indirect loss was about US$ 118,000 due to landslides with a 3-year return period. But when the median value of landslide volume was taken for each magnitude class, the TBT was estimated as 110 days for the railroad and 2 days for the road and total indirect loss was about US$ 30,840 due to landslides with a 3-year return period. The analysis shows that the indirect risk, which directly depends on TBT, is highly sensitive to landslide volume and TBT.

For this study the estimated risk to life calculated for the road and train users are found to be below the tolerable limit based on the criteria given by AGS (2000). However, these criteria may not be applicable in India, in general and in the Nilgiri area, in particular and the boundary limits of the tolerable or intolerable risk may be different. The results show a low risk to train users but every attempt should be made to keep the risk as low as possible. Risk reduction is technically feasible along the entire railroad by means of slope treatment works. Another risk mitigation strategy is to reduce the probability of a train being below a landslide when it occurs, for example, closing the railroad during periods of heavy rain. This will lead to a temporary loss of revenue to the railway but such loss may be worth accepting when there is a greater risk of losing lives in an accident. At present the railway authority reduces the risk to train users by closing the railroad during the periods of heavy rain. The estimated risk will help to perform the cost-benefit analysis.
of these risk mitigation strategies and to formulate the cost effective measures to be adopted in order to reduce landslide risk along the transportation lines.

6.4.2 Risk estimation for natural terrain

For elements at risk located on a natural terrain, I have presented a model to quantify risk in both initiation zones and run-out paths of potential landslides. Estimation of risk considering the run-out is important particularly if the area has a potential for debris slideflows. I have attempted to demonstrate that it is feasible to estimate the range of expected losses for both initiation and run-out of landslides with different sizes. Although the method has several limitations, for example it is not suitable for estimating direct risk to moving vehicles and commuters, and indirect risks, however the method is suitable for assessing direct risk for individual elements at risk by considering the run-out distances. This method is also applicable for risk analysis in a large area where the interest is on assessing the hazard at the location of the elements at risk. Thus, if a hazard mapping is carried out with the aim to analyze risk then it is reasonable to use the proposed run-out model the way it is used here to estimate risk to the exposed elements rather then incorporating run-out distance itself in the susceptibility model.

The estimation of run-out distances was carried out manually starting from those elements at risk that are located down slope of areas with low, moderate and high susceptibility for landslide initiation. This procedure could be automated using a GIS. Since the run-out risk depends on the maximum run-out distance, therefore a certain degree of uncertainty is induced due to the estimated value obtained using Eq. (5.9), which is lower than those measured in the field. However, due to the large variation in the measured run-out distances it was reasonable here to consider the best-fit value.

The ultimate aim of a quantitative risk analysis is to facilitate financial and cost-benefit analysis for planning risk reduction strategies. For this the risk should be expressed as annualized loss. For an optimal estimation of annualized loss landslide of different sizes and their annual probability of occurrence should be analyzed. However, such an analysis requires a substantially complete landslide inventory for a long period of time, which in fact is seldom available at least for landslides affecting natural slopes covering a large area. The proposed method fulfils the gap of data scarcity and provides a possibility of estimating landslide risk on natural slopes based on more complete information of landslide in untreated excavated slopes along roads and railroads in the same area. Since roads require immediate clearance therefore maintenance records are expected to be more complete.
The highest loss was estimated for buildings followed by tea/coffee plantations, railroad, road and least for the horticulture plantations. The level of expected annual losses of buildings and tea/coffee plantations is comparable as plantation has a larger spatial coverage and 92% of the buildings were located in low susceptible zones. It should be noted that the expected losses for plantations and the total loss given in Table 6.7 could be much higher if we estimate the risk of landslide run-out for this. The estimation of run-out risk to plantation areas requires information on the total deposition (inundation) area of potential landslide debris and since the proposed run-out model does not show area likely to be inundated therefore the run-out loss to plantations remains unestimated.

Although I initially expected that run-out losses will be greater than initiation losses but the results show that the total annual average run-out loss is only 10% of the total annual average initiation losses. This is because for run-out losses I presented only those elements (buildings and infrastructures) that are located down slope of susceptible initiation areas and I also have not included run-out losses of plantation areas. But for a number of individual buildings the run-out losses are greater than the initiation losses. The average and maximum run-out losses are greater than the respective initiation losses for all buildings except those in Burliyar and Marapallam, which are located in high susceptible slopes. Run-out losses are much larger than initiation losses for the average and maximum landslide magnitudes because of their long run-out distance and higher probability of reaching the elements at risk. This difference is relatively small for the minimum landslide magnitude except in Kallar area where the initiation loss is larger than the run-out loss.

The societal risk shown in Figure 6.11 indicates that the risk of one or more lives lost is high in all settlements for which the run-out risk is analyzed. In comparison to the F-N curves from other countries as shown in Duzgun and Lacasse (2005), the estimated risk for 100 or more lives lost is lower than for China and for Japan but higher than for Nepal and for Italy. For 10 or more lives lost the value is lower than Japan but higher than Nepal, Columbia and Italy. It is to note that this comparison may not be the true representation because in other countries researchers might have used different risk assessment approaches.

There are several inherent uncertainties in the methodology as well in the data used in the risk analysis which I have tried to quantify by estimating ranges of expected losses. Uncertainties are related with the inherent assumption of the models, estimation of probabilities and various
assumptions made in order to simplify the risk analysis. These uncertainties may be of considerable significance and are inherent to risk estimation to landslides (Bell and Glade, 2004). It is important to indicate these uncertainties in order to inform end users of what is known, what is unknown and what is only partially understood (Stern and Fineberg, 1996).

Medium to very high uncertainty is associated with the hazard estimation as discussed in Section 5.5.2. Use of magnitude classes also introduces uncertainty in the hazard analysis. Since it is difficult to analyze risk for every landslide size therefore the choice of magnitude classes is optimal and the uncertainty is inevitable. However, I have included these uncertainties in the risk analysis by defining a range of possible values. I quantified the uncertainty by considering the minimum, average and maximum landslide sizes in each magnitude class and the corresponding minimum, average and maximum run-out distances and vulnerability values. The uncertainty in the direct risk to properties located on natural slopes is in the order US$ 224,000 (difference between the total annual maximum and the total annual minimum loss). In fact the uncertainties can be modelled using different scenarios based on ranges of values and using simulation methods such as a Monte Carlo simulation, which can be taken up in a further study.

A high uncertainty is also associated with the calculation of the population risk. This is mostly related to the estimation of the probability a person will be killed given that the building is impacted by a landslide. Uncertainty in $P_{pop:bt}$ is less as it is easier to estimate based on occupancy type and number of people.

Methods for landslide risk assessment should always take these uncertainties into account and should be feasible to implement over larger areas without excessive requirements on data amounts. The uncertainties must be included in the analysis and the results should be expressed as a range of risk values as demonstrated in this study where I estimated the range of expected losses for both initiation and run-out of landslides with different sizes. Considering the uncertainties associated with various input data used in the risk analysis, it is advisable that for planning of risk reduction strategies a detailed risk assessment in a large scale must be carried out.

The estimation of direct risk is more straightforward than the indirect losses. An indirect loss to someone could be of advantage to others, for example a fuel shop located on an alternative route may earn more due to road blockage and additional fuel consumption, and similarly a transport company can earn profit through additional ticket costs and local vendors by increasing
the price of commodities. It is rightly pointed out by researchers such as van Westen et al. (2006) that the risk formula looks deceptively simple, but once put into practice it quickly turns out to be very complicated and a lot of aspects need to be taken into account which are often difficult to evaluate.

As a final output the study provided risk curves, total annual loss and F-N curves. The total annual loss obtained in this study may be higher if we include direct loss to vehicles and commuters, and indirect loss due to landslides initiating on natural slopes. Since, the information on the frequency of landslides (number of slides per annum) and the total volume of debris on the (rail) road per return period was not available for the hazard on natural slopes, therefore direct risk to vehicles and commuters, and indirect risk remained unestimated. However, the obtained result may form the basis for a cost-benefit analysis and for designing risk reduction measures based on risk acceptance criteria i.e., defining the limit of the acceptable and tolerable risk. At present there are no landslide risk tolerance criteria available in India and thus, the future work should focus on the development of one such criteria otherwise we cannot assess the landslide risk.
Landslide Risk assessment
Chapter 7: Validation of hazard and risk models

According to the guidelines of the Joint Technical Committee on landslides and Engineered Slopes (Fell et al., 2008) all models used in the hazard and risk analysis need to be validated for their performance in forecasting landslides. Validation of results of a predictive modelling is absolutely essential in order to make the model applicable for practical purposes. Without some kind of validation, the prediction model has no scientific significance (Chung and Fabbri, 2003).

Validation can be performed using a variety of datasets, but for practical purposes, validation can best be performed using landslide events independent from the ones used in modelling landslide hazard and risk (Chung et al., 1995). What we require is the spatio-temporal information on landslides and resulted consequences that have affected the area after the period considered in constructing the models.

Researchers commonly follow four different methods to obtain an independent landslide dataset for validation purposes: (i) they split the landslide inventory into two sets, one set used as calibration dataset for modelling and other set as validation dataset; (ii) modelling is carried out in one part of the study area and the model is extrapolated to the other part of the area where it can be validated using landslides belonging to the validation area; (iii) modelling is carried out using landslides that occurred in a certain time period and validation is performed using landslides of a different period; and (iv) validation is carried out using landslides that occurred after the period considered in the modelling. The latter is most adequate to test the validity of the “prediction” made, but as a disadvantage it requires a landslide event to occur.

In this chapter a temporal validation (of type iv, see above) is made of the models presented in the previous chapters. This is based on a number of landslide events from November 2009, for which the rainfall characteristics and the type of damage caused will be presented first. The chapter will also account experiences of people who witnessed these events. Finally, the 2009 landslide events will be used to validate the rainfall threshold model, the landslide size probability model, the susceptibility model, and the hazard and risk models.
7.1 Landslides triggered by rainfall on November 2009

In the period between January 2008 and December 2009, a total of nine landslide events have affected the Nilgiri district, out of which the landslide event that occurred on 8, 9 and 10 November 2009 is the severest in terms of the number of landslides triggered and damage caused. On these three days continuous heavy rainfall triggered numerous landslides within the study area around Hillgrove and Katteri, and adjacent to the study area around Wellington, Ketty and Lovedale. The three days cumulative rainfall was recorded as 202 mm at Kallar farm, 387 mm at Burliyar, 560 mm at Hillgrove, 865 mm at Katteri farm, 937 mm at Coonoor and 1357 mm at Ketty rain gauge. The amount of rainfall shows a dramatic decrease from West (Coonoor) to East (Kallar farm) of the study area. The heavy precipitation in a short period resulted in flash floods and torrent streams, which triggered landslides along the channels and the accumulated debris flowed down slope causing damages to properties located close to stream courses.

Figure 7.1 shows examples of the type of landslides triggered and the damage caused in this event. Landslides were mostly debris slides and debris flowsides of sizes ranging from M-I to M-IV (Table 4.2). At many places unsupported cut slopes with thick overburden cover failed, such as around Lovedale (Figure 7.1A-C), Katteri (Figure 7.1D) and Marapallam (Figure 7.1E). At Lovedale, two houses and parts of the railroad were damaged due to a debris slide triggered on a cut slope (Figure 7.1C). At Marapallam, a debris slide from a road cut completely damaged buildings located below the road (Figure 7.1E). In the Ketty area a debris slide initiating from natural slopes (Figure 7.1F) destroyed several houses located along its flow path (Figure 7.1G). The runout of the debris flowslide was to a distance of 500 m. Around Coonoor most damage was caused by torrent streams containing landslide debris, for example, a swimming pool (Figure 7.1H) and cottages (Figure 7.1I) of a hotel were damaged by a torrent stream. Similarly, in Katteri area, torrent streams removed the support of a house (Figure 7.1J). At some places, even small landslides caused extensive damage to houses (Figure 7.1K) and loss of human lives (Figure 7.1L).

Figure 7.2 shows an example of the landslide damage due to inadequate land use practices. Residents of a village near Coonoor have diverted a stream and constructed houses along its flow path (Figure 7.2A). On 9 November 2009 several small debris slides were triggered in the upper reaches of the stream resulting in a huge debris flow. The debris followed the stream course and
caused severe damage to houses located on its natural flow path (Figure 7.2B).

Figure 7.1 Examples of landslides triggered in 2009 and damage caused (see text for explanation).

At two places people were interviewed that had witnessed the landslide event on 10 November 2009 at 0045 hours. In the Katteri area, an owner of a car workshop woke up at midnight due to the unusual barking of his dog, and when he came out of his workshop he heard a cracking sound of falling debris and noticed very high discharge in the nearby stream (Figure 7.3). As he
Validation of models

unlocked the door, the dog hurriedly ran out of the house. The owner and his family immediately followed the dog and by the time they were 50 m away, they noticed landslide debris, carried by the stream, destroying their workshop and four parked cars. In another incident at Ketty, a resident witnessed landsliding shown in Figure 7.1F. According to the eye witness, a large landslide occurred in the very early morning of 10 November 2009. The landslide initiated above the road on a natural slope due to very heavy rainfall (820 mm in one day) and partly blocked the road thereby creating artificial damming of water accumulated along the road to a distance of about 100 m. After a few minutes the temporary dam breached causing a debris flow, which destroyed several houses along its flow path (Figure 7.1G).

![Figure 7.2](image)

*Figure 7.2* Damage to houses located on the natural flow path of a stream. The houses shown in circle 2 and 3 were completely damaged killing one woman. The houses shown in the circles were reconstructed in 2010.

For these events a landslide inventory was prepared from the railway slip register and landslide technical reports. Field mapping was carried out in February 2010. A total of 147 landslides were identified and spatially mapped on a 10,000 scale topomap. Figure 7.4 shows the spatial distribution of landslides triggered in November 2009 and Table 7.1 gives their statistics. Landslides on cut slopes were mapped as points and on natural slopes as polygons. Out of the 147 slides, 71 occurred on cut slopes along the railroad and 65 along the road, and 11 on the natural slopes around Katteri and Hillgrove area. Field evidences indicate that most landslides on natural slopes...
were caused due to erosion (over bank or head ward) by torrent streams. A total of 80 landslides on cut slopes were reactivated old slides whereas 67 landslides, including all landslides on natural slopes, occurred in locations without clear evidence of previous landslides. Prior to November 2009, seven more landslides have occurred along the railroad, which makes a total of 154 landslides in 2009.

Within the study area the total physical damage caused by the 2009 landslide events include five houses, two shops, two cottages of a resort, one workshop, one tourist restroom, four parked cars, two parked trucks, one swimming pool. The events caused seven human casualties. Besides, the NH-67 road was closed for 57 days, and the railroad from Coonoor to Kallar was closed for 157 days, thus resulting in both direct and indirect losses.
Validation of models

Table 7.1 Statistics of landslides triggered by the November 2009 events.

<table>
<thead>
<tr>
<th>Attributes</th>
<th>nr</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of landslides</td>
<td></td>
<td>147</td>
</tr>
<tr>
<td>Total landslides on cut slopes</td>
<td></td>
<td>136</td>
</tr>
<tr>
<td>Total landslides on natural slopes</td>
<td></td>
<td>11</td>
</tr>
<tr>
<td>Volume of smallest landslide</td>
<td>m³</td>
<td>2</td>
</tr>
<tr>
<td>Volume of largest landslide</td>
<td>m³</td>
<td>3,600</td>
</tr>
<tr>
<td>Average volume of landslides</td>
<td>m³</td>
<td>224</td>
</tr>
<tr>
<td>Median volume of landslides</td>
<td>m³</td>
<td>70</td>
</tr>
<tr>
<td>Standard deviation of landslide volume</td>
<td>m³</td>
<td>518</td>
</tr>
</tbody>
</table>

7.2 Validation of rainfall threshold models

In Section 4.1.3.3, I showed a method to validate a rainfall threshold model and gave examples using landslide events from 2001, 2006 and 2007. Here, I use landslide events that occurred after 2007 for validating the model performance for future forecasting of landslides. For the validation, I use the same method as discussed in Section 4.1.3.3. The crossover of the threshold curve from negative to positive values is taken as an indication of the conditions favourable for landsliding. One or more landslide events are expected before the positive curve decays to the zero threshold value.

Out of the nine landslide events recorded in 2008 and 2009, five have occurred in the period between October and December 2009 due to the retreating monsoon. These five landslide events were used to validate the threshold models on cut slopes (Figure 4.3) and the model for natural slopes ($R_T = 210 - 0.54 R_{5ad}$). The results are shown in Table 7.2. The probability of occurrence of landslides given the exceedance of the thresholds that can trigger less than 15 landslides on cut slopes within units I to VIII, $P[L|(R > R_T)]$, varies from 0.20 to 1. In terms of percentage, the forecasting accuracy

Figure 7.4 Spatial distributions of landslides caused by the 2009 events.
for most models for small landslide events (< 15 slides) remains less than or equal to 50%. The performance of the model is better for rainfall events that can trigger landslides on natural slopes and 15 to 90 failures on cut slopes (threshold for the entire route). The threshold model \( R_T = 220 - 0.61 R_{5ad} \) for the entire route and model \( R_T = 210 - 0.54 R_{5ad} \) for natural slopes give probability of \( P[L|(R > R_T)] \) equal to 1, which indicates that the threshold model is capable of accurately forecasting landslides of large events. The low performance of the models in units I to V is because of small threshold limits which are attributed to even a single slope failure on cut slopes.

Figure 7.5 shows the performance of the threshold model for natural slopes during October to December 2009. In Burliyar area, landslides occurred on 10 November when the rainfall crosses the threshold value, whereas in Hillgrove and Runnymede landslides also occurred on 8 and 9 November when the threshold was high. In the Kallar area, rainfall did not cross the threshold value and also no landslide occurred in this part of the study area (Figure 7.4). Similarly in 2008, the threshold was not exceeded in any of the rain gauges and therefore no landslide occurred in this year.

The probability of occurrence of one or more landslide events on natural slopes in a 3-year time period was estimated high (~0.65) in sections I and III and relatively low (~0.33) in sections II and IV (Table 5.7). However, in 2009 rainfall triggered landslides in all sections, except in section I. An amount of rainfall similar to the 2009 events has never been recorded during the period of analysis (1987 to 2007). In the recent past, a very high rainfall occurred in 1979 that resulted in floods and landslides around Coonoor area (Seshagiri and Badrinarayan, 1982).

### 7.3 Validation of landslide size model

In this section, I compare the results of the probability of landslide size discussed in Section 4.3.4 with the result of 2009 events. Figure 7.6 shows the non-cumulative probability density distribution of landslide volumes of the 2006 and 2009 events computed using Eq. (4.5). In 2009, the probability density distribution shows a distinct change in slope of the curve for failure volumes less than 200 m³ whereas in 2006 a roll-over in form of flattening of curve was observed for failure volumes less than 200 m³. However, in both distributions the linear portion of the curve (volume > 200 m³) are comparable and shows a negative power law fit with \( \beta = 1.7 \) in 2009 and \( \beta = 1.9 \) in 2006.
Validation of models

Table 7.2 Validation of exceedance of rain threshold and occurrence of landslide events during 2008 and 2009 (RR = Railroad, NS = Natural slopes).

| Units*         | Threshold equation | Number of times the threshold exceeded | Landslide frequency in units | $P[(L | R > R_T)]$ |
|----------------|--------------------|----------------------------------------|-----------------------------|-----------------|
| RR I           | $R_T = 66 - 0.93 R_{Sad}$ | 5                                      | 1                           | 0.20            |
| RR II          |                     | 5                                      | 2                           | 0.40            |
| RR III         |                     | 5                                      | 1                           | 0.20            |
| RR IV          | $R_T = 165 - 1.32 R_{Sad}$ | 4                                      | 1                           | 0.25            |
| RR V           |                     | 4                                      | 1                           | 0.25            |
| RR VI          | $R_T = 230 - 1.32 R_{Sad}$ | 2                                      | 1                           | 0.50            |
| RR VII         | $R_T = 250 - 1.5 R_{Sad}$  | 2                                      | 1                           | 0.50            |
| RR VIII        |                     | 2                                      | 2                           | 1               |
| Entire railroad| $R_T = 220 - 0.61 R_{Sad}$ | 1                                      | 1                           | 1               |
| NS Kallar      | $R_T = 210 - 0.54 R_{Sad}$  | 0                                      | 0                           | 0               |
| NS West of Burliyar |               | 1                                      | 1                           | 1               |

* for units along the railroad refer Figure 4.6.

Figure 7.5 Validation of the threshold equation $R_T = 210 - 0.54 R_{Sad}$ for natural slopes. Positive values on the y-axis indicate threshold exceedance ($R > R_T$).

The probability of a landslide volume exceeding 1,000 m$^3$ is estimated as 0.04 in 2009, which is smaller than that observed in 2006 (0.07). In fact in 2009, small landslides (volume < 100 m$^3$) occurred in relatively large number. This is because in 2009 most landslides occurred within section III and IV (Figure 4.1), which have gentle slopes covered by tea plantation. A similar case was observed in 1993 (see Section 4.3.3) where the gentler terrain of section IV triggered more small landslides and resulted in a negative power law distribution of landslide volumes.
For cut slopes, the probability of occurrence of landslides in 2009 was found to be 0.61 for < 100 m$^3$, 0.35 for 100 to 1,000 m$^3$ and 0.04 for > 1,000 m$^3$, which is significantly different from the values used in the hazard model on cut slopes for years with more than 100 landslides i.e., 0.39 for < 100 m$^3$, 0.53 for 100 to 1,000 m$^3$ and 0.08 for > 1,000 m$^3$. As explained above the greater percentage of small slope failures is because of the gentle terrain condition. The percentage of landslides of larger volume would have been more if the same amount of rainfall that triggered landslides between the Marapallam and Katteri section would have affected the area east of Burliyar where slopes are steeper and the height of cut slopes is more.

![Figure 7.6](image)

**Figure 7.6** Probability density distributions for the landslides that occurred in 2006 and 2009.

### 7.4 Validation of landslide susceptibility model for natural slopes

The most common approach used to validate a susceptibility model is the use of a “prediction rate curve” (Chung and Fabbri, 2003). In this section, I determine the ability of the susceptibility model, obtained using logistic regression analysis (Figure 5.10), to predict future landslides in the study area. In order to analyze the prediction skill of the susceptibility model, I use source area of landslides on natural slopes triggered by 2009 landslide events.
Validation of models

and the model proposed by Chung and Fabbri (2003). The model involves computing the proportion of the event landslide area in each susceptibility class, and showing the results using cumulative statistics.

Figure 7.7 shows the percentage of the study area, ranked from most to least susceptible (x-axis), against the cumulative percentage of the area of the triggered landslides in each susceptibility class (y-axis), as a dashed black line. The prediction rate curve shows that the most susceptible 20% of the study area contains 65% of the landslide source areas shown in Figure 7.4. This 20% of the susceptible areas also contain the high susceptible slopes that are located east of the study area. The model is able to predict about 67% of the landslide areas as unstable group (spatial probability > 0.6). Further, the most susceptible 33% of the study area contains 77% of the landslide areas whilst 80% of the landslide areas are predicted by most susceptible 40% of the study area. Most of the landslides shown in the inventory map (Figure 7.4) are in areas classified as susceptible by the model, although still 12% of the slope failures are in areas with an estimated probability ≤ 0.20. The prediction of the model is better than the success rate in the high susceptible areas. It is reasonable to accept that if a rainfall event triggers landslides equally in the eastern part of the study area then the prediction rate could be much better. In 2009, even some of the low susceptible areas covering tea plantation also experienced landslides. Very high rainfall on 9 and 10 November 2009 triggered slope failures even in gentle slopes.

The result shown in Figure 7.7 provides a quantitative estimate of the model prediction skill. Since the aim of susceptibility modelling is to forecast the spatial location of future landslides, therefore, it is obvious that the model prediction rate should always be better or equivalent than its success rate. In this validation test the prediction of the susceptibility model is better than the model fitting performance shown in Figure 5.11 at least for the high susceptible areas. Contrary to this, others researchers (e.g., Chung and Fabbri, 2003; Guzzetti et al., 2005) have observed that the prediction rate of a susceptibility model is often lower than the success rate of the model. They argued that since the success rate measures a "goodness of fit" assuming that the model is "correct" therefore the success rate is always better than the prediction rate for any study area.
7.5 Validation of landslide hazard and risk models

The validation of a hazard and risk model for different temporal scenarios is difficult because it requires information on landslides of different time periods that have affected the area after the period considered in the analysis. In a short time period it is highly uncertain to have information on landslide events of different return periods. However, the availability of information on landslides that occurred in 2009 provided an opportunity to validate the hazard and risk models, at least for the available small period of time.

Using the landslide events of 2009, I attempted to validate the results of the Gumbel analysis used to quantify hazard along the transportation lines i.e., the number of landslides per kilometer of cut slopes in different return periods. Table 7.3 compares the results of the Gumbel analysis (Figure 5.3) with the occurrence of landslides per kilometer of cut slopes along the railroad in 2009. The table indicates that for km-17, km-19 and km-20, the number of landslides that occurred in 2009 corresponds to a return period of 25 or more years. The amount of rainfall that triggered landslides in this section of the railroad (i.e., 865 mm around Katteri farm) has never occurred in the period considered in the modelling (i.e., 1987 to 2007) but was known to have occurred in 1979 (Seshagiri and Badrinarayan, 1982). The recurrence
Validation of models

of a landslide event after 30 years thus validated the results of the Gumbel analysis between km-17 and km-20 along the railroad.

**Table 7.3** Validation of the landslide hazard along the railroad.

<table>
<thead>
<tr>
<th>Kilometer</th>
<th>Number of landslides per return period (year)</th>
<th>nr of slides in 2009</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>10</td>
<td>6</td>
<td>9</td>
</tr>
<tr>
<td>11</td>
<td>6</td>
<td>10</td>
</tr>
<tr>
<td>12</td>
<td>7</td>
<td>10</td>
</tr>
<tr>
<td>13</td>
<td>5</td>
<td>8</td>
</tr>
<tr>
<td>14</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>15</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>16</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>17</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>18</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>19</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>20</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>21</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>22</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>23</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>24</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>25</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>26</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>56</td>
<td>84</td>
</tr>
</tbody>
</table>

In most of the other railroad sections between km-10 and km-17 (i.e., around Burliyar) the number of landslides that occurred in 2009 corresponds to a much lower return period (5 years or less, Table 7.3). Although these sections are more prone to landslides (Figure 5.3) but the amount of rainfall that triggered landslides in these sections in 2009 was comparatively less than those recorded around km-19. In fact the rainfall decreased sharply from Coonoor towards the East. The amount of rainfall recorded in Burliyar on 10 November 2009 was 192 mm. Rainfall events with this amount have actually occurred three times in the past 21-year period (1987 to 2007), which corresponds to a recurrence interval of seven years. The seven year return time of the landslide triggering rainfall events corresponds well with the result of the Gumbel analysis for the section of the railroad located between km-10 and km-17.

A total 78 landslides occurred along the entire railroad in 2009, which is comparable to the result of the Gumbel analysis for a 5-year return period (i.e., 84 landslides). It is reasonable to accept here that if the entire area would have received the amount of rainfall that triggered landslides around Katteri farm (corresponding to a landslide event with a 25-year return period), then the total number of landslides would have been much higher.
(around 160) as predicted by the Gumbel analysis for a scenario with a 25-year return period.

Along the road, the occurrence of 65 landslides is comparable with the model output for a 25-year return period (66 landslides). The occurrence of more landslides between km-390 and km-414 (S-II) triggered by extremely high rainfall corresponds to an event similar to the one from 1979.

Examples in literature that show the validation of a hazard map using landslide events that have happened after the production of the map (the so-called “wait-and-see” method) are very few. In most landslide hazard publications, researchers have shown only the validation of a susceptibility map. Since the hazard models discussed in Section 5.3.1 are dependent on the three probabilities i.e., the size, the temporal and the spatial, therefore validation of the three probabilities as discussed in Sections 7.2, 7.3 and 7.4 reasonably accounts the predictive capability of the hazard model.

Validation was not possible for the risk models due to the unavailability of data on the losses that occurred in 2009. According to the model, the total direct loss for a 5-year return period along the railroad is estimated as US$ 202,000 and disruption of the rail traffic for about 200 days. In fact due to the 2009 events the railroad was closed for 157 days. The higher value for the estimated route blockage is resulted because of low coefficient of correlation (0.65) of the relation between the total volumes of debris (in m$^3$) on the railroad and total blockage time (days) used in the analysis.

In case of risk due to slope failures on natural slopes, the obtained risk can not be validated because there are no available data on landslide losses available for the entire area. However, the losses to buildings caused by the 2009 landslide event (see Section 7.1), if quantified, may be comparable to the minimum expected losses of a 25-year return period because landslides triggered in 2009 are individually small in size (< 5,000 m$^3$).

### 7.6 Discussion and conclusions

Validation of hazard and risk models is often difficult due to the lack of sufficient validation datasets. Though the availability of information on 2009 landslide events has given the opportunity to validate the models but still we have to “wait and watch” for more events to occur in order to validate the hazard map for different time scenarios.

For the validation of the complete study area, it is essential to have a validation dataset that is spatially distributed throughout the study area. It is
Validation of models

also essential that the landslide triggering condition used for validation should be similar to the one used in the model, which is the basic assumption of the hazard modelling. The landslide events of 2009 occurred due to an extremely high rainfall and affected mostly the western part of the study area. The lack of data in the eastern part makes it practically difficult to validate the susceptibility and the hazard of areas located east of Hillgrove. Difficulties also arise due to a large spatial variability of rainfall over the area. As observed in November 2009, one part of the study area (East) experienced landslide events with a 5-year return period, and at the same time another part (West) experienced events with a 25-year return period. This makes the hazard and loss estimation for the entire area very difficult.

The validation of the prediction skills of all models used in the hazard analysis appears to be reasonable for the given limited time period. The result of the success rate of the susceptibility model (i.e., 73% of the landslide areas occurring within class having spatial probability > 0.6) is comparable to the prediction made by the model (i.e., 67% of the landslide areas of 2009 occurring within class having spatial probability > 0.6) and therefore the distribution of landslides shown by the success rate provide a good approximation of the distribution of future landslides in different susceptible classes within the study area.
Chapter 8: Use of landslide hazard and risk information

Hazard and risk information is generated for a variety of objectives within the framework of Landslide Risk Management (Figure 8.1). These objectives have implications for the scale of mapping, the quality and type of information available and the methods used for hazard and risk analysis. In Figure 8.1 three main objectives for Risk Reduction area are indicated: emergency preparedness, land use zoning and engineering solutions using cost-benefit analysis for the design of structural risk reduction measures. The success of the use of hazard and risk information in reducing risk to the communities relies on the priorities of the implementing authorities, the availability of resources and the perception of the local people towards landslide risk.

In this chapter the three above mentioned uses of hazard and risk information in risk reduction will be treated. For emergency preparedness the perception of the local Nilgiri communities towards landslide risk will be evaluated and simplified maps are generated for the benefit and understanding of end users. A rainfall threshold-based early warning system will be presented, which could be used in risk awareness programmes involving public participation. Quantitative risk information is also used for the planning of structural measures to protect the road and railway alignments, and examples are shown how the transport organizations could implement these measures. Finally also hazard and risk information can be used for spatial planning and zoning, indicating areas where the landslide hazard is too high for planning future developments.

8.1 Introduction

Landslide Risk Management (Figure 8.1) essentially involves identification, estimation and evaluation of the risks, implementations of risk reduction options and balancing the different components of cost in an acceptable way (Crozier, 2005). Figure 8.1 also indicates that environmental changes in India due to global change and resulting reactions in ecosystems, combined with expected changes in socio-economic development will lead to adjustments in land use in areas that are exposed to mass movements. These hazards will also have domino effects (e.g., the effect of land use change such as deforestation on creating more severe landslide hazards). The effects of these changes need to be analyzed and modelled with probabilistic hazard and risk methods that can be used by stakeholders from different sectors. The probabilistic models should incorporate the uncertainties in temporal probability, spatial extend and magnitude of the hazards, as well as the
Use of models

uncertainties of the vulnerability of the exposed elements at risk. The modelled changes in hazard and risk patterns need to be incorporated into disaster risks management strategies and will form an important factor in land use planning activities at stakeholder relevant levels. They also have a large impact on risk governance policies that need to be adapted.

Within the risk assessment framework shown in Figure 8.1, the estimated risk needs to be evaluated by comparing the output of the risk analysis against values of judgement and risk tolerance criteria to determine if the risks are low enough to be tolerable (Fell et al., 2005). For example, in case of risk to life, the communities assess risk from a given landslide as acceptable or non-acceptable by evaluating the losses against the benefits that they obtain in the particular locations (Bromhead, 1997; AGS, 2000). Such evaluations require interplay of various organizations where the judgement takes into account political, legal, environmental, regulatory and social factors. Assessment of all these factors for evaluation of risk is beyond the scope of this work, but for the benefit of the end user we can illustrate the use of the obtained landslide hazard and risk information in various risk reduction measures for the optimal management of landslide risk.

Once the risk analysis is completed for an area the next step of risk management is to use the hazard and risk information to take measures to reduce risk to the community at risk (see Figure 8.1). Crozier (2005) listed nine different approaches to mitigate landslide risk. These approaches essentially work towards either reducing the probability (the temporal, the spatial and the size) of occurrence of hazard in a given location by means of various mitigation options or reducing the vulnerability of elements at risk such as through improvements of the physical built-up environment by making them more resistant to the possible landslide impact. Risk mitigation can also be carried out either by reducing the amount of elements at risk in hazard areas such as by relocation or by increasing risk awareness among the people at risk through education. The nine approaches mentioned in Crozier (2005) can be grouped into three strategies: land use zoning, engineering solutions and emergency preparedness.
Land use zoning is the most economical and effective means of reducing future landslide losses. In land use zoning risk reduction can be achieved for existing elements at risk that are located in high hazard zones by relocating them to hazard free areas. However, practice has shown that this is very difficult to implement. Therefore land use zoning is more appropriate for defining restrictive zones where new constructions are not allowed. In fact relocation of elements at risk is often not a real option because people do not want to relocate, unless the local authorities offer economically much more favourable alternatives. To make this option viable the strategy should involve the affected stakeholders and the public in the planning process because the public is more likely to comply with the policies if they feel that they have some ownership of the process and have input into the plan. Furthermore it is often the public who have to meet the cost of risk reduction measures. Susceptibility maps are used in defining a building permit system.
Use of models

encompassing both permits for construction a building in a particular location, and the type of building (building codes). The permit system restricts or regulates new developments, such as construction of roads, buildings, irrigation, etc., in landslide susceptible areas. It can carry instructions such as constructions are only allowed in low landslide susceptible areas whereas appropriate slope treatments are mandatory in moderate susceptible areas, and no constructions are allowed in high susceptible areas. In fact, it is important to have national guidelines for landslide risk management, which should be implanted at local scale. One such guidelines is now available in India, which is called National Disaster Management Guidelines published by the National Disaster Management Authority (NDMA, 2009).

Engineering solutions, such as restoration and slope stabilization works, construction of drainages, etc., are often used to reduce landslide risk by minimizing the probability of landslide occurrence. Landslide mitigation using engineering solutions is expensive and is generally suitable for a few known unstable slopes as it is difficult to delineate the precise location of potential landslides and areas affected by potential debris flows at a catchment scale. Nevertheless, the type of engineering solutions to be adopted is decided after evaluating the cost-benefit ratio of the desired solution and for that information from quantitative risk models are used.

Emergency preparedness, denotes the ability of a community to put into action established plans and procedures (Crozier, 2005). This strategy tends to reduce the risk by increasing awareness among the public with an aim to timely respond to the warning when the disaster strikes. Preparedness essentially includes public awareness education programmes and understanding of warning system for timely response. There can be different types of early warning systems for landslide forecast such as those for an individual landslide to warn people about the movement of specific landslide based on movement sensors, etc., or those for communities or organizations for small areas (using simple thresholds and rain gauges) or those for large areas (like a weather prediction for very high rainfall which could be potential for triggering landslides). The most cost-effective means of an early warning system is those based on rainfall/landslide relations through the use of a rainfall threshold (Keefer et al., 1987; Aleotti, 2004). Warning system can provide information on when landsliding would occur and this in conjunction with hazard maps can delineate potentially hazardous areas (Dai et al., 2002). The public awareness education programmes are often carried out under the community based disaster management programme (CBDMP) which includes participatory mapping exercises, mock drills for emergency response, etc. (Chen et al., 2006).
The choice of the type of measures depends on the preference of the decision-makers, who are normally expected to use hazard and risk information to arrive at a conclusion. But, for a successful risk mitigation involvement of local communities in the decision making is equally important (Pearce, 2003). If local communities are ignored, then chances of providing reasonable solutions to disaster-related problems are often decreased and in many instances the decisions and actions taken by the planners are challenged thus creating an atmosphere of conflict, delay of the mitigation plans and increase of mitigation cost. Thomas (1995) presented a number of ways of involving the public in the decision making process such as through public meetings, surveys, advisory committee, etc. If communities are to be involved in the planning processes then it becomes necessary to understand the perception of the local population and their needs for managing risk.

8.2 Evaluation of landslide risk perception

This section summarizes the findings of the landslide risk perception surveys that were carried in the Nilgiri area. The objective was to understand the perception of the people towards landslide risk, which will later help in selecting appropriate strategies of risk reduction in the study area. The perception to landslide risk depends on the cultural perspective and background of the people. Harmsworth and Raynor (2005) discussed five situations which, in general, contribute to an increase in people's perception to landslide risk. These include perception of risk formed from loss of natural resources, from impacts on economic assets and production loss, from experience of an actual damaging landslide event, from damage of cultural features or icons, and from education or community participation. In the Nilgiri area people are aware of landslide risk because landslides occur very frequently in the area and cause substantial damage to life and property. In the study area perception of risk is formed mainly from experience of the actual damaging landslide events in recent past (e.g., 1993, 2006 and 2009), from the loss of production and business due to road blockage and from the risk awareness programme undertaken in the schools and local communities.

For the perception study, a questionnaire survey was used in order to understand the local communities’ interest in the landslide disaster-related problems. The survey was carried out at 12 locations (settlements) in the Nilgiri area and the local population were interviewed in groups. The targeted groups had a different social and economic status in the communities, such as labourers, businessmen, servicemen and school children. The locations were selected such that one group represented people who had witnessed or experienced landslides in 2009, one group of people located in landslide hazardous area (e.g., residents located in Katteri, Figure 3.13), one group of
people who had witnessed landslides in past (e.g., residents located in Marapallam), one group of people who have never experienced landslides and are located in safe areas (e.g., residents of Adderley area), a group of people involved in businesses (e.g., shop owners at Katteri and Burliyar) and a group representing educated school children. The questionnaire was designed to obtained information on peoples’ perception about landslide risk, their pre-disaster preparedness, methods for transferring warning information, and strategies they use to reduce and mitigate landslide risk. The same set of questions was used for interviewing people in all locations. Since the questions were in English therefore I personally interpreted the questions for their understanding and selected answers that represented the common opinion in the groups. The questionnaire is provided as annexes in the supplementary CD-ROM. The objective behind surveying people with different economic and educational status and having recent or past or no landslide experiences is to observe the change in the perception of people to landslide risk as a result of recent loss or impact of landslides.

The important findings of the questionnaire survey are:

1) Most people of the Nilgiri area are aware of landslide disasters and they accept the fact that their area is prone to landslides,
2) They are aware of the cause of landslides (i.e., very high rainfall) and they know that the period between October and December is the most problematic,
3) They are not able to indicate the areas that could be the a potential source of landslides (susceptible slopes),
4) People do not appreciate/understand technical terms such as landslide disaster readiness, disaster preparedness, susceptibility, probability of death, etc.,
5) Most of the people have lived in the study area all their life and their ancestors for many generations and in spite of the fact that they have experienced or witnessed landslide disasters they do not want to leave their native place,
6) People tolerate the risk because of certain benefits such as working in nearby tea plantations, running businesses along the road, etc.,
7) People perceive landslides as an “act of God” and they believe that only wrong doers will be affected,
8) They have no emergency preparedness plans and insurance coverage of properties for a landslide disaster,
9) They depend on the local government and local organizations such as Rescue Operation Unit, a non governmental organization, for post disaster help and mitigation,
10) The low economic status of most communities does not permit them to carry out additional investment for reinforcement of their houses in order to protect them from landslide damages, and

11) People agree to provide services and land for installing monitoring devices for landslide warning, for example drillings were carried out at nine locations in the Katteri area on the private property for instrumentation for landslide monitoring.

The study indicates that irrespective of their economic status people are conscious about the landslide problems and they consider that the local administration is responsible to take up necessary measures to make their houses safer from landslide disaster. People want timely information on expected landslides in their area and the know-how to reduce and mitigate landslide risk. In many cases it was observed that people are ignorant about what to do and no to do during a landslide disaster, for example the resident of the house shown in Figure 7.2 (circle 1) ignored the unusual sound of debris that damaged his house. From the interview it is evident that most people lack knowledge about different precautionary measures to be followed during a high rainfall event, except for schoolchildren and people who have taken part in the disaster management programmes conducted by the Rescue Operation Unit.

Besides local people, authorities such as railway, road and local administration were also contacted in order to understand their perception to landslide risk. The authorities view landslides as a persistent problem in the Nilgiri area. They are willing to find out feasible solutions to the landslide problems in order to safeguard the local population from landslide disaster.

### 8.3 Planning risk reduction strategies

Landslide hazard and risk information are the outcome of scientific analysis of various geo-environmental and landslide damage data, and normally these can be best interpreted by the geo-scientists who developed the models. If such results are to be used by non-scientific communities then in addition to the scientific content it is essential to provide results in a format which non-scientific users can understand. There can be different types of end users depending on the area of interest and the type of landslide problems. Therefore, it is important to identify potential end users and find out their requirements, and later present the results in terms that the user can use.

In the study area several end users are defined as indicated in Table 8.1, which also summarizes the requirements and purposes of different end users. Table 8.1 clearly indicates that end users can be geo-scientists (Geotechnical
Use of models

unit), engineers (Railway and Highway units), businessmen (tea estates) or common people with little or no education. Their requirement varies depending on the type of work they do. Therefore, information should be provided according to their needs in order to make the hazard and risk maps understandable and applicable to the end users.

<table>
<thead>
<tr>
<th>Table 8.1 Different end users and their requirements.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>End user</strong></td>
</tr>
<tr>
<td>Railway unit and Highway unit</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Geotechnical unit (a landslide investigation Cell of Government of Tamilnadu)</td>
</tr>
<tr>
<td>Tea estates</td>
</tr>
<tr>
<td>Rescue operation unit (a non governmental organization)</td>
</tr>
<tr>
<td>Local people</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

8.3.1 Land use zoning

For planning land use zoning strategies we require information on the distribution of past landslides (inventory) and areas vulnerable to future landslides (susceptibility/hazard). Information on past landslides can be obtained from the landslide inventory map (e.g., Figure 3.8 and Figure 7.4). The inventory map helps to have accurate perceptions of where mass movements have occurred that posed threats to the communities. Such maps can provide valuable information for land use planning. For example,
recurrent damage from landslides can be avoided by evacuating areas that continue to have slope failures, and frequent landsliding areas can be prioritized for landslide monitoring and mitigation. A large scale inventory map showing slope failures of different time periods can be used to infer the evolution of landslides with time or to monitor changes in the area of landslides, which may pose danger to communities located nearby. For example Figure 3.13 shows the temporal evolution of landslides which pose a risk to residents located on the crown of the slide scarp. Such areas therefore require immediate mitigation.

Landslide inventories (Figure 3.8 and Figure 7.4) can be used by different end users to derive information specific for their work and requirements. Figure 8.2A shows an example of the type of information that the railway and road maintenance units can derive from the inventory. For example, the railway unit may not be interested in knowing the location of the landslide scars on hill slopes rather they will be interested to know which section of the railroad was affected. The figure shows the longitudinal section of the railroad between km-20 and km-21 and the sections that were affected by debris from cut and natural slopes. Such information can be used to locate sections where landslides have occurred in past and where they are expected to occur in future. If GIS is used then the multi-temporal information on landslides can be used to observe the active sections and the sections where landslides occur repeatedly thereby prioritizing the mitigation work (e.g., Figure 3.13). This information can further help to calculate the length of retaining wall needed to contain debris from the adjacent cut slopes.

Figure 8.2B shows the type of landslide information that the geotechnical units, tea estates and local communities can derive from the landslide inventory, depending on their area of interest. The area showing paths of debris flows and overbank erosion can be avoided for any future development and immediate actions must be taken to protect those slopes from further erosion in order to minimize the risk to properties located nearby (e.g., Figure 8.2C).

When interpreting a landslide inventory map one should remember that all landslides shown in the map may not persist and with time unstable slopes eventually get stabilized due to natural or man made actions. Also, if the map is not complete then one should be careful in interpreting areas where no landslide is shown. For the optimal use the inventory map should be updated after every triggering event and for this institution appropriate for the work should be identified. It is advisable to use such maps in GIS.
The information on landslide hazard (Chapter 5) can be used for planning future developments. The hazard provides information on areas prone to landslides in future, including the type of landslides, number of landslides and volume of debris expected.

Figure 8.3A shows the type of information that a geotechnical unit can derive from the landslide susceptibility map (Figure 5.10) and use it for issuing clearance certificates for safe building construction. The area can be grouped into different classes based on the relative likelihood of occurrence of landslides. The areas having a higher proneness to landslides are shown in red. Orange represents areas where chances of future landslides are lesser than red and green are the safe areas or areas having very low chances of occurrence of landslides. The red areas should be avoided for construction of new buildings, utility centres and communication infrastructures. Such areas can be used as open space, parks, woodland and recreation. In orange areas it should be mandatory to carry out basic stabilisation works before taking up any building projects. The green areas are relatively safe for construction of buildings. It should be noted that the orange or green susceptible areas can be affected by debris flows from upslope areas and therefore when interpreting the map the landslide travel distance (run-out) should be considered using the relation shown in Figure 5.14.
It should be noted that the map shown in Figure 8.3A is applicable for the present land use and environmental condition, and if the land use changes or new landslide information is available than the susceptibility map should be updated. Other than geotechnical unit, the susceptibility map can be used by the rescue operation unit, tea estates and the local communities to identify areas that are potential for future landslides within their area of interest. For example, such maps can be posted on a display board in the centre of the communities for warning against potential landslide disaster. The susceptibility map in combination hazard information, which shows the likelihood of occurrence of landslides within a given time period (Figure 5.13), can be used for a more rational planning of land use for a given design life of the project. Due to the inherent uncertainty I suggest consulting the three models (i.e., spatial, temporal and size probability) separately before drawing final conclusion about the site selection for a project. The above suggestion will help in analysing the hazard more rationally.

Figure 8.3B shows the type of information that the railway and road maintenance units can derive from the result of the hazard analysis. The figure shows the sections of the railroad between km-20 and km-21 prone to potential landslides derived based on the result of the susceptibility and the run-out model. Further information on the number of landslides and the total volume of debris expected in different return periods from cut slopes can be obtained using the hazard information (Figure 5.3; e.g., Table 5.2). This information can be used to estimate the minimum or maximum funds and manpower required to mitigate landslide disaster in a budget period. For example, an event with a 50-year return period (annual probability of 0.02), will result in a maximum damage and thus require the maximum allocation of funds and manpower. The results can also be used to identify sections where relatively more landslides can occur, given the threshold exceedance within a rain gauge area, and thus facilitates timely transfer of equipments to the nearest location for early clearance of the (rail) road. The results can also help in prioritizing engineering solutions for the sections of the (rail) road where the frequency of landslides are expected to be more (Figure 5.3; e.g., Table 5.2).

8.3.2 Engineering solutions

Engineering solution is the most direct and costly strategy for reducing landslide risk (Dai et al., 2002). It involves either correction of the underlying unstable slopes using methods such as modification of the slope geometry by excavation or toe fill, use of retaining structures, internal slope reinforcements, surface drainage, etc. or controlling of the landslide movement to reduce its impact on the elements at risk located downslope.
Use of models

Prior of considering the engineering solution for mitigation its feasibility study is carried out, including the cost-benefit analysis of the solution where information on risk is used as an input. Risk information can also be used to perform cost-benefit analysis for land use planning and improvement to building codes and critical infrastructure.

![Figure 8.3 Hazard information for risk reduction planning (see text for explanation).](image)

### 8.3.2.1 Cost-benefit analysis for planning engineering solutions

One of the important uses of quantitative risk information is in cost-benefit analysis for selecting a feasible mitigation measure. The quantitative risk analysis as shown in Chapter 6 provided the total annual loss, which is the basic parameter required to carry out such cost-benefit analysis. Below I provide an example where I demonstrated the use of the obtained risk results in selecting the cost-effective engineering solution for mitigating cut slope failures along the road and the railroad. The example only provides a rough estimate of the costs based on the available information and the actual value may differ depending on the specification of the measures, the extent of the area to be treated and implementation cost. Three engineering measures are considered:

1. Grass turf - the use of grass turf is not very common in the study area but in one experiment (Figure 8.4A) the feasibility of a grass turf in landslide mitigation along a road cut was tested. The process involves modification of the slope below the friction angle, which in this case taken as 30° angle, and then use of turf to cover the slope. The advantage of this method is that it doesn’t require periodic maintenance over a long period and since it involves flattening of slope therefore it is more reliable in containing shallow mass movements. As a disadvantage this method may not be feasible if the slope is steep and where flattening of the slope is difficult. The average cost of this measure is US$ 6.5/m², including the costs of flattening of slope.
2. Concrete retaining wall – this measure involves constructing a concrete retaining wall at the toe of the cut slope to stabilize slope failure. Figure 8.4B shows the concrete retaining structure constructed in 2010 to stabilize slope failures shown in Figure 3.13. The method is suitable along the road where availability of space permits construction of a retaining wall, however along the railroad the method is not very common due to the space limitations. The average design life of a retaining wall is 15 years. The advantage of this method is that it also doesn’t require continuous maintenance. But as a disadvantage since the maximum height of the structure is 3 m and therefore it may not be suitable for containing a large landslide. The average cost of this measure is US$ 69/m³.

3. Boulder gabion wall – this is the most common mitigation measure used in the study area. It is of low cost, the average cost is US$ 1.07/m, and is effective for small slope failures. The method involves stacking of boulders in a wire mess and the structure is used as a retaining wall for providing toe support. The structure has a design life of two years.

In cost-benefit analysis the cost is the one-time investment costs of the project and maintenance costs that arise over the lifetime of the project. The maintenance cost includes costs of the annual maintenance of the measures against landslide damage and clearance of debris overtopping the retaining structures. For this analysis the costs for maintenance are considered to be 1% of the project cost. It is assumed that these costs will increase with 5% each year. Benefits are taken as loss reduction i.e., the savings in terms of direct and indirect loss due to cut slope failures, which are estimated as the total annual loss. The total annual loss is about US$ 164,500, which include the loss of US$ 128,400 along the railroad and US$ 35,100 along the road.

Finally, costs and benefits have to be compared under a common efficiency criterion in order to be able to derive at a decision. Net present value (NPV) is one of the criteria, which is most commonly used in cost-benefit analysis (Crosta et al., 2005). Costs and benefits arising over the life time of the project are discounted and the difference taken, which is the net discounted benefit in a given project life. The sum of the net benefits is the Net present value. If the NPV is positive (i.e., benefits exceed costs), then a project is considered feasible to implement.

In order to perform the analysis several assumptions were made: the project will take an investment period of four years for turf for mitigating a 3.5 km of scars along the railroad, two years for turf for mitigating a 1.5 km and 2 km of scars along the railroad in different sections, two years for a concrete
Use of models

retaining wall and two years for a gabion wall for mitigating all 2.1 km of scars along the road. It is also assumed that after mitigation no major slide will take place.

The cost-benefit analysis was performed using excel for six scenarios considering the maintenance costs and investment periods as given above and 10% interest rate. NPV was taken as the criteria for comparison of feasibility of different measures and was calculated for a period considering the life time of the measures i.e., 15 years for turf and concrete retaining wall and two years for gabion wall. The six scenarios are:

- Scenario #1- the grass turf is applied for treating many landslide scars between km-10 and km-26 of the railroad. The benefit is US$ 128,400, which is the total annual loss due to cut slope failures along the railroad and the cost is US$ 455,000 for a combined scar length of 3.5 km.
- Scenario #2- the grass turf is applied for treating many landslide scars between km-10 and km-13 of the railroad, which is the maximum hazard section. The benefit is US$ 52,360 and the cost is US$ 195,000 for a combined scar length of 1.5 km.
- Scenario #3- the grass turf is applied for treating many landslide scars between km-14 and km-26 of the railroad. The benefit is US$ 76,040 and the cost is US$ 260,000 for a combined scar length of 2 km.
- Scenario #4- the grass turf is applied for treating many landslide scars along the road. The benefit is US$ 35,100 and the cost is US$ 273,000 for a combined scar length of 2.1 km.
- Scenario #5- a concrete retaining wall is constructed for treating many landslide scars along road. The benefit is US$ 35,100 and the cost is US$ 484,550 for a combined scar length of 2.1 km.
- Scenario #6- a gabion retaining wall is constructed for treating a 2.1 km long section with many landslide scars along the road. The benefit is US$ 35,100, which is the total annual loss and the cost is US$ 6,800.

The cost of the treatment of cut slope scars was obtained based on the data (per unit cost) provided by the highway and the railway office. Table 8.2 shows the result of the six scenarios. The remark indicates whether the project is feasible or not feasible. If NPV is positive i.e., benefits exceed costs then the project is considered feasible. Along the road the NPV was less than zero for turf (scenarios #4) and concrete retaining wall (scenarios #5) thus suggesting that these measures are not profitable. The first three scenarios (#1, #2, #3) along the railroad are profitable mitigating measures and therefore these can be tested. The analysis suggests that financially it is recommendable to apply grass turf for stabilizing unstable scars between km-
14 and km-26 of the railroad (scenarios #3). The result also suggests that since the NPV of scenario #1 is positive and comparable to scenario #3 and in scenarios #1 there is an advantage of mitigating all landslide scars along the railroad therefore it is more reasonable to use scenario #1 instead of scenario #3 for mitigating landslides along the railroad. But, the feasibility of these scenarios from geo-technical, environmental and engineering aspect should also be considered. For example, scenario #1 may not be technically feasible due to steep terrain rather scenario #3 is more technically viable.

Similar calculations can be performed for different slope stability measures using results of risk models. However, it may be noted that before selecting any mitigation measure the actual cost-benefit analysis has to be performed by professionals, using the actual estimated values of costs of measures, maintenance costs, investment period, interest rates, etc. One type of measures may not be suitable for the entire area, rather several different combination of mitigation measures can be considered depending on the type of elements at risk such as some slopes can be stabilized using grass turf while some using retaining wall or even cost-benefit analysis of option such as alteration of bridges, bioengineering solutions, measures like soil nailing, shotcreting, etc. can be carried out. Nevertheless, in all analysis information from risk models will form an important input.

Figure 8.4 Slope stabilization measures: (A) grass turf combined with retaining wall and (B) concrete retaining wall.
8.3.3 Emergency preparedness

8.3.3.1 Development of a landslide early warning system

One of the most cost-effective measures to reduce landslide risk to the communities in the Nilgiri area is the implementation of a simple landslide early warning system, in which the communities themselves play a major role. The work that has been presented in Chapter 4 on rainfall thresholds can be a good basis for the development of such an early warning system.

In several countries, rainfall thresholds have been used to forecast rainfall-induced landslides, particularly in the USA (San Francisco Bay area) (Keefer et al., 1987; Baum and Godt, 2009) and Hong Kong (Chan et al., 2003). The warning system is composed of several components, including the establishment of rainfall-landslide thresholds, rainfall forecasting methods, real-time rainfall monitoring and an automated computing system for evaluation of warning. The system is essentially based on a quantitative precipitation forecast using remote sensing data and a large network of automated rain gauges to issue warning message on threshold exceedence. The capabilities of warning rely on the empirical threshold model which can be based on various precipitation measurements such as antecedent rainfall, rainfall intensity and duration, cumulative rainfall and duration, and normalized rainfall, etc. The details of the types of threshold models used all over the world over can be found in Guzzetti et al. (2008). Landslide early warning systems can also be designed for individual landslides that have intermittent activity, e.g. using extensiometers to monitor slope deformation, or using cables with vertical rods to detect debris flows. However in the study area, nearly all of the major landslides are first event failures, and therefore the installation of such types of early warning systems is not feasible.

The warning system proposed here considers daily rainfall as there are no rain gauges that continuously record rainfall data. The model uses threshold rainfall, rainfall forecasts, probability of occurrence of landslides given the...
threshold exceedance, and hazard and risk models to issue an early warning of rainfall-induced landslides. The threshold is derived from the empirical relationship of 5-days antecedent and daily rainfall required to trigger landslides (see Section 4.1.3 and 5.3.1.2). The 24-hour rainfall forecast can either be based on the weather forecast by the Indian Meteorological Department (IMD) or it can be inferred from the rainfall and weather condition. Advanced techniques of rainfall forecasting such as the Doppler radar are not available for the study area. The warning system will essentially require the manual measurement of daily rainfall from different rain gauges and the comparison of the 5-days cumulative and daily/forecast rainfall with the threshold value to determine the threshold exceedance. The calculation of threshold exceedance can be performed automatically in an excel sheet, or on paper.

Figure 8.5 shows the criteria that can be used to issue different levels of warning of rainfall-induced landslides. The first warning line can be introduced slightly below the actual threshold line i.e., a limit which, if exceeded, activates the start of the warning procedure (Aleotti, 2004). When the recorded rainfall (X1Y1) crosses this limit at Phase-1 it starts up the warning procedure. At this stage ‘Watch’ warning can be issued cautioning the people that a critical condition of slope failure has reached and further rains may trigger landslides. From here threshold variation can be continuously monitored using different values of forecast rainfall. At this stage use of forecast rainfall is important in order to observe the trend of the rainfall in the next 24-hour hours. When rainfall in the next 24-hour is expected to exceed the threshold line or the current rainfall touches the threshold line (X2Y2) then Phase-2 warning (Alert) can be issued. The warning will alert the community about the possible occurrence of landslides. On further monitoring if the rainfall is expected to exceed further then the communities should be cautioned of major landslide events and instruct them to be prepared for immediate evacuation.

The warning for evacuation is not feasible using this system because it is very difficult to predict the precise location of landslide initiation based only on threshold information. The exact location of landslides is important if people are to be evacuated. In fact after the ‘Alert’ warning the people should be on the alert, and start looking for signs of instability, and then only evacuate. Since, exceedance of the threshold indicates that the condition conducive for landsliding has set in therefore after the ‘Alert’ warning people should start working with the disaster preparedness plan so that the loss can be minimized.
Use of models

Figure 8.5 Criteria that can be used to issue warning of rainfall-induced landslides based on rainfall threshold.

Operating procedure of the warning system

Figure 8.6 describes the conceptual operating procedure of the warning system. Its practical application is yet to be tested in the field. The warning procedure activates when the recorded 5-days antecedent and previous day rainfall passes the warning line. At this stage (Phase-1) a general warning ‘WATCH’ can be issued at least 12-hours in advance informing people that the rainfall condition is critical and slope failures may result if a similar rainfall condition continues. Warning should also contain information about emergency readiness, safe place for evacuation and precautions to reduce risk to life. This phase provides time to the authorities to disseminate information to the public and make equipment available for the potential disaster.

After Phase-1, continued monitoring of the threshold rainfall is carried out using different values of rainfall forecasts. During this time additional information is gathered such as the probability of occurrence of landslides given the exceedance (e.g., Table 4.1) in a given area. If the forecasted rainfall or the measured rainfall at a certain time touches or exceeds the threshold line then the ‘ALERT’ warning (Phase-2) should be issued informing the people about the specific areas where landslides can occur based on the obtained hazard information. At this stage people are advised to look for indications of landslides such as opening cracks, unusual sounds (rumbling/cracking sound of debris) and be prepared for evacuation if similar rainfall conditions persist. This phase gives relatively less time to the people and the authorities to react.
After Phase-2, variation in thresholds is continuously monitored using both measured and forecasted rainfall. At this time risk maps can be consulted and specific hazardous areas can be outlined. This phase requires very rapid assessment of specific hazard and risk because of the small reaction time and because of being in the instability field. If the rainfall decreases below the threshold line then the ‘ALERT’ warning can be withdrawn and if it increases further then the ‘ALERT’ warning remains and the authorities can simultaneously activate the emergency procedure such as rescue and mitigation.

Figure 8.6 shows a general operating procedure that can be used by any end user. However, depending on specific requirement and the type of risk to be reduced the operating procedure and the type of warning may differ. For example, for the railway even a small cut slope failure along the railroad will be disastrous and therefore the railway unit could like to use thresholds of small landslide events (< 15 landslides expected) for issuing the ALERT warning and stopping the train services. In contrast, for the small landslide events the highway unit can keep the road open for small vehicles but close the road if rainfall passes the threshold for the entire route (> 15 landslides expected). Table 8.3 summarises the activities of different end users during the warning phase. These activities are highlighted in order to ensure maximum reduction of risk due to landslides in the study area. In case of road stopping of all vehicles and closure of the road is advisable only if the ALERT warning is for the large event. This is because for small events the chances of occurrence of landslides after the exceedance of the threshold is less than 50% but for the large events the chances is 73% (see Table 4.1).

**Limitation of warning system and needs**

Warning systems for potential rainfall-induced landslides are technically feasible, however operational warning systems are practical only where the elements at risk make such systems cost-effective and the population is willing to respond to the warning issued (Baum and Godt, 2009). There can be several reasons which make the implementation of warning systems difficult. These include: limited resources, lack of data on hazard and risk zones, barriers to rapid communication in remote areas, lack of public awareness about potential landslide risk, and confusion about what landslide warnings means and what actions to be taken when a warning is in effect. Besides these practical difficulties, uncertainties in the warning system further make its implementation difficult. Frequent false alarms (warnings that are not followed by landslides) or landslides that occur without warning decrease the trust of the population in a warning system.
Use of models

Figure 8.6 Operating procedure of warning system based on rainfall thresholds.
Table 8.3 Type of end users and their activities during warning phase.

<table>
<thead>
<tr>
<th>User</th>
<th>Threshold for warning</th>
<th>Area of warning</th>
<th>Type of failure</th>
<th>Warning phase and type of warning issued</th>
<th>Activities and Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Railway unit</td>
<td></td>
<td></td>
<td></td>
<td>WATCH</td>
<td>ALERT</td>
</tr>
<tr>
<td>$R_T = 66 - 0.93 R_{50d}$</td>
<td>East of Burliyar</td>
<td>Cut slope</td>
<td>Active vigilance and patrol</td>
<td>Stop train services</td>
<td>Resume services after end of the ALERT warning</td>
</tr>
<tr>
<td>$R_T = 165 - 1.32 R_{50d}$</td>
<td>Around Hillgrove</td>
<td>Cut slope</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R_T = 250 - 1.5 R_{50d}$</td>
<td>Around Marapallarn</td>
<td>Cut slope</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R_T = 230 - 1.32 R_{50d}$</td>
<td>West of Runnymede</td>
<td>Cut slope</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R_T = 220 - 0.61 R_{50d}$</td>
<td>Entire railroad</td>
<td></td>
<td></td>
<td>Close railroad</td>
<td>Mobilization of man power for the railroad clearance</td>
</tr>
<tr>
<td>Highway unit</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R_T = 66 - 0.93 R_{50d}$</td>
<td>East of Burliyar</td>
<td>Cut slope</td>
<td>Active vigilance and patrol</td>
<td>Stop public buses and mass transport vehicles, only small vehicles allowed to pass but with caution,</td>
<td>Emergency vehicles on standby at different locations, deployment of bulldozers at safe locations, Resume services after end of the ALERT warning</td>
</tr>
<tr>
<td>$R_T = 165 - 1.32 R_{50d}$</td>
<td>Around Hillgrove</td>
<td>Cut slope</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R_T = 250 - 1.5 R_{50d}$</td>
<td>Around Marapallarn</td>
<td>Cut slope</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R_T = 230 - 1.32 R_{50d}$</td>
<td>West of Runnymede</td>
<td>Cut slope</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R_T = 220 - 0.61 R_{50d}$</td>
<td>Entire road</td>
<td>Cut slope</td>
<td></td>
<td>Stop all vehicles, road closed</td>
<td>Mobilization of man power for the railroad clearance</td>
</tr>
<tr>
<td>Local communities</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R_T = 210 - 0.54 R_{50d}$</td>
<td>Study area</td>
<td>Natural slope</td>
<td>Inform family members, collect emergency supplies, first-aid, etc.</td>
<td>Be on high alert, Start looking for signs of instability, and then only evacuate</td>
<td>Evacuate schools and other buildings with many people that are located in potential hazard zones,</td>
</tr>
<tr>
<td>Local administration</td>
<td></td>
<td></td>
<td></td>
<td>Issue of 'WATCH' warning message</td>
<td>Issue of 'ALERT' warning message</td>
</tr>
</tbody>
</table>
Use of models

Development of a clear warning language and instructions that are appropriate to the locality and its population are essential for the successful implementation of an early warning system. Publications on language and statements for different levels of warning are available (e.g., Keefer et al., 1987). Warning should essentially include instructions such as “does and don’ts” during an imminent landslide disaster, indications/signs to recognize a landslide (e.g., cracks, rumbling/cracking sound of debris), and indication of safe areas. It should also include a description of the expected hazard, delineation of the affected area, appropriate actions, how long the warning is valid and contacts for more information.

For the study area, the following text of the warning could be used for the ‘WATCH’ category if the local communities are to be warned:

“Due to continuous rainfall in Area-A of Coonoor subdivision, there is a possibility of occurrence of landslides in the area (or along the road/railroad section between km-Xa and km-Xb) if the rainfall continues to remain same or increases further. People living in this area are advised to be cautious, be prepared with emergency supply kit, should watch for any pre-landslide indications and inform their family members about the nearest safe ground. Keep listening to your news media for further information”.

For the ‘ALERT’ category following text can be adapted:

“A warning of a level ‘Alert’ is hereby issued to people living in Area-A. Due to continuous rainfall, the potential for landslides has increased and people should be aware that a similar rainfall in past had triggered slides. Persons in the warning areas should be prepared to move to safer ground immediately if similar rainfall condition continues to exist for next few hours. Watch out for signs of landslides till rainfall subsides. Keep listening to your news media for further information”.

It is important that the warning message should reach to the people concerned within a stipulated time. The risk perception survey indicates that people prefer electronic media (television) more than radio or internet. It is advisable that an alternate medium of warning should be established in case of power failure, which is common during very heavy rains. One way is to use Short Messaging Service of mobile telephone or through representative identified in each community for transferring of the warning messages.

8.3.3.2 Public awareness and education programme

For successful implementation of warning systems, and other risk reduction measures, a public education program is essential to ensure that residents of landslide prone-areas understand the landslide hazard, its causes, the appropriate precautions, and actions that should be taken to prepare for and
respond to landslide events. There are several ways to make people aware of the potential landslide disasters. More commonly it is done without involving the public directly in the awareness programme such as by issuing instructions through print or electronic media, representatives or social workers, pamphlets, etc. This type of approach is fast and cost-effective but does not ensure that people will actually receive the information. Alternatively more effective methods are those that involve the public directly. Through community participation programmes people can be educated interactively about the potential hazard, appropriate actions required on warning, alternate safe routes, first-aid, etc. Even the risk perception surveys suggested that the local populations want more interactive awareness programmes in order to learn about the risk reduction methods.

Community based disaster management programmes (CBDMP) can be grouped into different types depending on the way the community is involved (Chen et al., 2006). A description of all the types of CBDMP and their implementation is beyond the scope of this research, however here two disaster preparedness approaches are presented that have been tested in the study area:

1) Participatory mapping exercises, which help in educating local people on the potential landslide hazard, alternative routes for evacuation and disaster preparedness, and
2) Mock drills, which include training of government officials and local population on search and rescue and first-aid.

The earlier risk awareness programmes were based on historical knowledge of landslides in the area, but with the availability of the hazard and risk maps it is now possible to incorporate knowledge of future risk scenarios. Information from the hazard and risk assessment should be included in the participatory mapping exercises and landslide experts should be involved in the CBDMP.

**Participatory mapping**

The aim of these exercises is to obtain local knowledge of individuals and communities about the nature of the threat, and its potential impact, the options for reducing the risk or impact, and how to carry out specific mitigation measures. It is also aimed to obtain views from the community about their disaster experiences, collect information about past landslide events and their impact, determine aspects that contribute to vulnerability, determine feasible risk reduction scenarios and their risk reduction strategies in an informal, flexible and relaxing atmosphere. The important activities here
Use of models

include mapping of hazard and risk, vulnerabilities, safe and alternative routes, and the preparation of a village level disaster management plan solely based on public experiences.

The following activities are required for the participatory mapping exercises:

1. **Orientation**: At first stage an orientation programme is conducted where people can be briefed about the importance of the exercise, about landslide phenomena, a warning system, risk preparedness, their responsibilities, etc. It is expected that when the people understand the goal of the exercise and benefits they will participate more actively. Figure 8.7A shows photograph of the orientation programme that was conducted in the study area by the Rescue operation unit of Coonoor. The first challenge here is to bring people together for the participation. The most effective way is to involve local administration at the beginning. This gives a sense of trust and importance to the programme if the officials are involved and the people take the event more seriously. Other incentives, such as free refreshment, certificate of attendance, etc. are provided, which also ensures people participation. In fact the local government allocate funds to hold such programmes at a regular interval.

2. **Mapping landslide hazard and risk**: in this stage people are asked to draw a sketch map of their locality and identify the landslide areas based on their experiences. The mapping helps those who have not experienced landslides such as new residents and the younger generations to understand the landslide problems in their area. The mapping can be done on paper, or using large prints of high resolution photographs on which people can recognize buildings, roads and fields. However it is also possible to make these maps by drawing them with chalk on the ground, which has a better visibility and gives the opportunity for more interaction. At this stage, potential landslide hazard and susceptible areas can also be added based on the information from the hazard and risk analysis described in the previous chapters. Information should also be exploited to identify areas at risk for the run-out of debris flows in addition to areas where landslides may initiate. Figure 8.7B shows a field photograph of the mapping exercise undertaken by the local community in the study area.

3. **Mapping alternative routes and safe shelters**: the third stage consists of the identification of alternative evacuation routes and safe shelter places drawn by the people based on their local knowledge of the terrain. At this stage, landslide experts are required to evaluate the places and routes drawn by the people for the potential landslide risk. Figure 8.7C shows a
field photograph of people drawing evacuation routes in their locality and Figure 8.7E shows the paper representation of these routes and safe shelters prepared by the people living in the Burliyar community.

4. **Problem appraisal and developing solutions:** At this level the community should develop a list of problems based on the above exercises. The community under guidance of experts should discuss the problems and probable solutions or ways to lessen the impact. It is important that the community identifies its own strategies using its own reasons and mitigation goals and outlines a framework for a community-based disaster management plan for risk reduction.

5. **Identification of representative:** The final step in this process is to identify a representative within each community who can liaison with the local officers and emergency management personnel during pre and post disaster phases.

**Mock drills**

The purpose of mock drills is to provide the local community with the basic skills that they need to respond to their community’s immediate needs in the aftermath of a landslide disaster, when emergency services are not immediately available. After discussing with the local people and understanding their needs, the planning team can set up courses targeted at search and rescue, first-aid, and time management. Trained emergency personnel, including local fire-fighters and emergency medical service personnel, supervise the mock drill. Figure 8.8 shows field photographs of the mock drill organized at Coonoor on 27 July 2007.
Use of models

Figure 8.7 Participatory mapping exercises (photographs provided by the Rescue Operation Unit, Coonoor).
Figure 8.8 Mock drills (photographs provided by the Rescue Operation Unit, Coonoor). Search and rescue (A-D) and first-aid (E-F).

8.4 Discussion and conclusions

The ultimate goal of any risk analysis is to reduce the risk to the communities living in the area, or to the population passing the area along the
Use of models

transportation lines. In case of landslides the objective of analysing hazard and risk in an area is to utilise the result in selecting appropriate landslide risk reduction strategies. However, this does not happen always and most often results of the hazard and risk analysis remain at an academic level. At least in India, though landslide studies have been carried out for many years but still their direct application in land use planning and pre-disaster management are not well recognized. The under or non utilization of results of hazard and risk analysis could be due to several reasons, including difficulties in understanding the scientific content/meaning of the models, and lack of information on the practical significance and utility of the models. Thus, in order to make the results usable, it is important to specify their practical significance and utility in the field. This will certainly lead to more acceptance and application of the results by planners and stakeholders.

The perception study highlighted different aspects of how people perceive landslide risk. People's perception changes and often increased if they have experienced damaging landslide events or if their properties are at risk, for example after the 2009 landslide event the owner of a Katteri property was willing to invest in the mitigation measures even without support of the government. Unlike flood and earthquakes, which have widespread consequences, landslides have localised effects therefore they are viewed more as a personal problem rather than a societal issue. The study showed two aspects of people’s perception of landslide: first, they perceive landslide as a natural disaster, and most of the communities are aware of the landslide phenomena, its causes, period of occurrence, etc. Such perception arises mainly from their past experiences and education. Second, most people show ignorance about the threat and do not have pre-disaster preparedness plans. The second aspect is more common in the society because of the low economic status of the people and also from the fact that people are unaware of the threat from landslide initiating in areas located away from their dwellings. The economically 'poor' people, such as labourers are more concerned about issues such as health, housing, employment, education, household incomes, etc., than the environmental or disaster issues. Similar perception is seen in other part of the world (e.g., in New Zealand) where livelihood takes precedence over the environmental issues in poorer section of the society (Harmsworth and Raynor, 2005).

Risk perception can also be learned over time through education and collaborative learning through community participation. The study showed that in most cases people are unaware of what to do and not to do during a landslide disaster and also they are ignorant about the stability of their surrounding areas. Disasters like 2009 can be averted if the people become
aware of the potential threat. Therefore efforts must be made to bring pre-disaster preparedness studies into the school curriculum. In fact, school plays an important role in the risk awareness process. Through awareness arising at the school level, not only the most vulnerable part of the population (children) is reached, but through the children also their parents can be targeted. School children can also be taught to look for signs of potential instability (cracks, disrupted vegetation, blocked drainage) and report these. Once the perception of communities and individuals of landslide risk is understood, it is then easier to facilitate and plan remedies and solutions to lessen the risk.

The study demonstrated some of the important uses of hazard and risk information in planning risk reduction measures. Though cost-benefit analysis suggests that engineering solutions can be used to mitigate landslide hazard but still complete removal of hazards is not always feasible (Stanganell, 2008), therefore effort must be towards reducing the vulnerability through awareness and warning system so that the coping capacity of the communities’ can be increased.

In this chapter an early warning system for landslides was presented to reduce the loss of life due to disastrous landslides. The use of an empirical threshold is a fundamental element of the proposed warning system. In Chapter 7 the efficacy of the empirical threshold models to forecast landslides in 2009 was demonstrated. However, it is important to understand that the empirical relationship between rainfall and landslide occurrence is a simplification of the actual phenomena (Aleotti, 2004).

Effective implementation of the proposed warning system requires significant resources. These include personnel for rainfall monitoring at all rain gauges, updated landslide hazard and risk maps, means to disseminate warnings, experts to interpret results, scientific rainfall forecasts, etc. Most of these resources are not always readily available and therefore efforts are needed first to establish the operational infrastructure and involvement of dedicated professional staff in order to provide reliable early warning of landslides. In case if it is not possible to create a separate infrastructure at this stage with dedicated staff for the early warning then it is advisable to implement this system at the community level. The railway and highway units can use thresholds for cut slope failures and their rain gauges to issue warning to regulate traffic movement while the local communities can use the rainfall information from the tea estates located within their community to issue warning locally. No doubt the latter case requires participation of the local communities and therefore CBDMP is so important.
Use of models

Our responsibility, as a geological community, should not be confined to the production of scientific maps and models but also to ensure their practical utility through active participation in educating planners and engineers about the types of hazard facing their communities (Howell et al., 1999). Through participatory exercises and trainings it is possible to make the communities aware of potential hazard areas, to strengthen their capability to resist landslide disasters and to develop an organization in order to carry out risk reduction actions. However, according to the Rescue Operation Unit, the involvement of local communities in the exercises and mock drills is a challenging job as people are often not willing to participate. It was evident in the 2007 CBOP that after orientation only few people accepted to act as victims and few tried to react according to the situation, but many people stood and watched the incident as spectators only.

Based on the knowledge gained in this research I conclude that for risk reduction more priority should be given in increasing awareness among people through CBDMP about the potential danger and ways to reduce risk. The frequency of CBDMP activities should be increased such that all communities living in landslide prone areas should be educated, for at least once.
Chapter 9: Conclusion and recommendations

In this chapter a brief discussion on the research questions will be presented. The conclusions will be drawn and general recommendations will be proposed about the data collection and the analysis of landslide inventory prepared from historical records, about the landslide hazard and risk analysis, and the landslide risk reduction. The conclusions will be drawn on what was presented and discussed in the previous chapters, and the recommendations will be based on the experience gained in landslide studies during this research and other works carried out in India. Finally, topics for future work in continuation of this research will be presented.

9.1 Appraisal of the research questions

The research aimed to address two important research questions: first, whether it is possible to obtain a substantially complete landslide inventory using only historical records and second, whether the obtained inventory can be used to quantify landslide hazard and risk. The research clearly demonstrated that for specific cases such as along transportation lines a substantially complete landslide inventory can be obtained using historical records belonging to the road maintenance units. The obtained inventory can be used to quantify risks from the cut slope failures along the transportation lines and from the natural slope failures in areas encompassing the transportation lines even if the landslide inventory in the latter case is incomplete.

At the initial phase of the research the first four research questions (Section 1.3) were obvious given the uncertainty of the availability and the quality of the historical records. Since all historical records were not purposely meant for landslide studies therefore identification and mapping of landslides based on the information given in the records was not trivial. Nevertheless, the records proved optimal for the purpose of inventory mapping particularly along the transportation lines (Answer to question # 1). The two important types of information obtained from the historical records i.e., the date of occurrence of landslides and the volume of landslides formed the basis for establishing the relationship between rainfall and the landslides, and between the frequency and the volume (Answer to question # 2). The availability of continuous records of landslides on cut slopes facilitated detailed analysis of the frequency-size relationship of landslides, which provided new insight into landslide volume-dependency on intensity of rainfall and on the local terrain condition. The relationship between rainfall and landslides further facilitated estimation of the temporal probability of occurrence of first-time slope failures on natural slopes, which was otherwise difficult to estimate.
Conclusion and recommendations

The research question related to the choice of the hazard method was reasonable given the type of landslides and the quality of information available in the study area. The occurrences of landslides on natural slopes as first-time failures and on cut slopes as reactivated failures make it reasonable to use different approaches to quantify hazard in both cases (Answer to question # 3).

The landslide inventory along the transportation lines provided a good estimate of the number of landslides in different return periods on cut slopes which further facilitated the estimation of the number and sizes of future landslides expected on natural slopes and the estimation of hazard (Answer to question # 4). The information on the number of future landslides made the estimation of landslide risk feasible in the study area.

The last question (# 7) related to the use of hazard and risk information in managing landslide risk was addressed on chapter 8 and several examples were shown where hazard and risk information could be used because of the availability of historical records. This is especially the case for the design of a warning system for rainfall-induced landslides.

In next section, I make appraisal of the objectives that were formulated in order to find feasible solutions to the proposed questions given in Section 1.3.

9.2 Landslide inventory

Although it is difficult to obtain a substantially complete inventory for large areas due to the lack of good records, but as demonstrated (Chapter 3) it is possible to generate such an inventory for small areas, particularly along transportation corridors, provided that maintenance records are available. It is important to rely that all landslides do not leave morphological signs recognizable for many years. Particularly small landslides get obliterated very fast, and once the vital information on landslides is lost the landslide locations remain unmapped both in space and time. Therefore landslides have to be mapped soon after every triggering event before the debris is removed naturally or by human. Normally for a large and disastrous landslide event funds are made available for the procurement of remote sensing data and mapping of landslides, but small and high-frequency events resulting in fewer landslides are often left unrecognized. Accurate and complete event inventory maps are possible only if landslides are mapped immediately after the event, and therefore if remote sensing data is not available for small events, then I recommend to systematically record (manually)
relevant information (including damage) on all landslides soon after the landslide-triggering event.

If mapping is to be done manually then it is not feasible for any single agency or a geo-scientist to collect landslide data after every triggering event and for all areas. The activity has to be made multi-disciplinary where different institutions should be given the responsibility of mapping landslides after every triggering event, at least along transportation corridors or in accessible areas. For this the non-professionals, e.g., local communities or schoolchildren, should be motivated and trained for reporting new landslide events. At present few institutions are engaged in landslide mapping within the study area but they have their own rules and restrictions on data sharing. This results in the loss of time in locating landslide data sources and in obtaining relevant permission for the data sharing. Since these data are of high societal significance, I, therefore, recommend establishing a defined repository where each institution should catalogue their landslide data for a scientific use.

Transferring information contained in historical records to spatially locate landslides is not a trivial task (Chapter 3). Difficulties occurred due to several constraints, related to (1) difference in the type of data available in the records, and (2) the quality of information e.g., in some records landslide location is referenced based on signs that got altered with time. A proper description of landslide location and a standardization in the inventory are essential for easy compilation of data and mapping of landslides, and therefore I recommend all institutions to use a common inventory for recording landslide data in the field and also recommend to specify location of landslides based on signs that are easily recognizable and reproducible even after long time and if GPS is available then best is to provide the coordinate of landslides.

A landslide inventory map has many uses. It can be used by another user for purposes other than the one for which the map was originally prepared. Therefore for better clarity, the landslide inventory map should specify the characteristics of a landslide catalogue, its completeness, quality of the data, and methods used to compile the information, including the inherent uncertainties and limitations. I recommend that, when preparing a landslide inventory map from historical records, the detailed characteristics of the data sources, approach used to identify the landslides and possible sources of uncertainties should be clearly specified.
Conclusion and recommendations

One of the exclusive uses of a historical landslide inventory is to establish a threshold rainfall for precipitation-induced landslides (Chapter 4). The threshold analysis can be further improved if a higher resolution rainfall data (e.g., hourly rainfall) is made available and the relation between rainfall intensity and hourly duration is established. Since rainfall-landslide relationship is a key factor used to compute probability (temporal) of occurrence of landslides based on threshold analysis, therefore for a better temporal model, I recommend establishing of at least one Automatic Weather Station (AWS) within landslide prone areas in order to have records on at least hourly precipitation.

In Chapter 4, I showed that the thresholds are dynamic and vary with changes in the local terrain conditions at least on cut slopes. For the same landslide event, different areas have different threshold values for landslide initiation. Since landslides are localised phenomena related to certain terrain conditions, therefore, I recommend not to use any regionally-derived thresholds for predicting landslides. Rather attempts must be made to obtain envelope curves for the study area itself or to use curves belonging to a nearby area having geo-environmental conditions similar to the study area. Similar to thresholds, expected landslide sizes also depend on the rainfall intensity and on the local terrain condition. Here I also recommend not using any regionally-derived probability density functions of landslide volumes for predicting the size of future landslides.

9.3 Landslide hazard analysis

In Chapter 5, I proposed methods to quantify landslide hazard. On cut slopes landslides occurred with a high frequency with an average rate exceeding 40 landslides per year. In contrast landslides on natural slopes were much fewer in number (considered as a “rare” event) and are mostly first-time failures. Along transportation line landslides occur mostly as a result of human disturbances (slope modification), a condition which is different from natural slopes. For this reason I primarily recommend to evaluate hazard separately for landslides initiating from cut slopes and from natural slopes. Depending on the scope of the work, type of the data available and the ultimate goal to be achieved, the methods for the hazard analysis may also be different. In Chapter 5, I showed that the primary objective of the hazard analysis along the road and the railroad is to quantify the number of slope failures for different return periods because landslides occur repeatedly along different sections of the transportation lines and with different frequencies. This objective was different than those meant for analyzing hazard on the natural slopes, where the inventory was incomplete. Because of these reasons I intended to use different methods for the analysis of
landslide hazard. Along cut slopes a direct relation via the number of landslides per unit length for different return periods can be made. For natural slopes this has to be done indirectly either by relating to the rainfall thresholds or by assuming the number and sizes of landslides in different return periods.

The success and accuracy of a hazard model rely on the completeness of the inventory. An incomplete inventory will result in incorrect prediction of the temporal probability of slope failures if the probability is calculated based on the recurrence of landslides. As a basic requirement, such model requires continuous records of all landslides within the time series such as those available for the railroad. Therefore, for this reason I recommend that if landslides are reactivated phenomenon in an area then calculation of hazard based on the recurrence of landslides should be attempted if a substantially complete landslide inventory is available. However, the fact remains that such an inventory is seldom available for a catchment scale.

In many instances, susceptibility maps are directly used for planning purposes. This often happens because of the lack of sufficient data for hazard analysis. In any case, the model must be verified for its prediction skills before accepting it for future analysis.

With the use of GIS, there is always an opportunity to derive and use a large number of landslide preparatory factor maps for modelling landslide susceptibility. However, as suggested by Carrara et al. (1995) and Guzzetti et al. (1999) care must be taken to select only those factors that bear a clear physical relationship with mass movement in the study area otherwise the result could be erroneous. Therefore I recommend carrying out spatial association tests, as shown in Section 5.3.1.3, for the optimal selection of input factor maps for modelling landslide susceptibility.

Theoretically, a hazard model provides more relevant information required for a land use planning. The susceptibility map gives estimated probability that the pixel will be affected by a future landslide, but the “future” here is not connected to a time period such as the next 5 years or 50,000 years. When the susceptibility is converted to hazard, the probability values are then connected to a time period, say during the next 25 years. In hazard, the temporal aspect of landslides (i.e., when a landslide will occur in any given area) becomes an important parameter and therefore I recommend validating the forecasting capability of the model on which the temporal probability is based upon. If the temporal probability is based
Conclusion and recommendations

on a threshold rainfall then the prediction skill of the threshold model should be validated if new event data become available.

As a general recommendation, if end users intend to use only the susceptibility map for risk reduction planning then I recommended in Chapter 8 (Section 8.3.1) that no public or personal utility projects should be allowed in highly susceptible areas, strict building safety regulations should be followed in moderate susceptible areas and constructions with simple slope stability measures be allowed in low susceptible areas. This is a general recommendation related to the landslide susceptibility based on the present land use condition, however it is to understand that the susceptibility values can be lowered if proper mitigation measures are adopted such that a high susceptible area can be made less vulnerable to landsliding. In case if the susceptibility map is used in future planning then I recommend that the susceptibility map showing the potential landslide initiation areas should not be used alone for planning but rather limits of potential debris flows should also be marked for the specific planning site using a run-out model.

In fact hazard maps are focusing more on problems, and convey a negative message (e.g., you are not allowed to build in certain locations) whereas most of the users are interested in future developments and positive aspects, without being hindered by restrictions. Therefore such maps might perhaps be focusing more on identification of safe areas and solutions for protection against landslides than simply outlining areas where further development should not be allowed.

9.4 Landslide risk estimation

The estimation of landslide risk to different assets, including the population, remains an ultimate goal of all the analysis aimed at mitigating the consequences of landslides. As compared to other hazards like flooding or earthquakes, landslide risk analysis remains a complicated procedure due to the localized nature of landslide events and the lack of data on intensity and vulnerability. The accuracy of the risk estimation relies on the quality and abundance of the damage information and reliability of the hazard model. The availability of damage information, including information on the landslide types, volume, velocity, intensity and kinetic energy at the time of the impact, is crucial for the assessment of vulnerability of elements at risk. However, damage catalogues containing information on all the above parameters are rarely available and for this reason vulnerability is often subjectively assessed.
In this study vulnerability was assessed both quantitatively (based on the damage data e.g., infrastructure) and subjectively (based on limited historic incidents) by taking only landslide size (volume) as a measure of landslide destructiveness. However, I recommend that if relevant and substantial information on landslide damages, including data on intensity, kinetic energy, velocity, etc. are available then vulnerability must be assessed considering the effect of all the parameters. But, the fact remains that systematic records of historical landslides and the damages caused are seldom available. Since such catalogues are extremely essential to determine landslide risk, I, therefore, recommend that resources must be made available for the preparation of historical catalogues of damages caused by landslides along with the other attributes of a landslide.

The risk models used in the study helped in the quantitative estimation of the direct risks to properties and population, and indirect risks resulting from the blockage of the transportation lines (Chapter 6). The estimation of risk is rather straightforward for those situations where potential landslides are expected to interact with the element at risk (e.g., landslides from cut slopes along the transportation lines) but complexities arise when an element at risk is located away from a landslide source and is at risk from a potential debris slideflow. In the latter case, it is essential to incorporate run-out distance in order to estimate the risk. I performed this operation manually and interactively but a more robust and automatic procedure is required for demarcating potential run-out zones and the inundation area. Furthermore, most of the empirical-based run-out models do not allow modelling many different scenarios including also the uncertainties of the input parameters, and also these models are good in back analyzing single source event, but not good in the forward prediction of multiple source events. For the latter case a good example is DFGridProb model (Horton et al., 2008).

Even after having a good knowledge, concept and understanding of risks, there is no method that guarantees an accurate estimation of landslide risk at a catchment scale. This is obvious given the variability and uncertainties associated with the input parameters. Therefore, I recommend incorporating the uncertainties within the risk analysis and providing a range of values which can be taken into account when the result is interpreted for land use planning. I also recommend that more detail risk analysis should be undertaken, case by case, at a larger scale for a rationale mitigation planning and development.
9.5 Landslide risk reduction

One of the main aims of the risk analysis is to help the society to recognize threats from potential landslides. As a final goal the estimated risk has to be reduced using methods that are cost-effective and easy to implement. I proposed to use an early warning system and community based participatory programme as a cost-effective approach to reduce landslide risk in the study area. A rainfall threshold-based warning system has never been implemented in the study area but the community based participatory programmes have been conducted in the past. The study of risk perception surveys and the landslide disaster of 2009 clearly indicate that the risk from potential landslides can be reduced if the communities become aware of the potential threat. Therefore, I recommend conducting Community Based Disaster Preparedness (CBDP) programmes at regular intervals, at least, in villages which are prone to landslide risk. The earlier participatory programmes were solely based on the local knowledge without incorporating information on potential landslide hazard and risks. I recommend including knowledge of the hazard and risk studies within the CBDP programmes as ‘mandatory’ for the societal benefit.

Implementation of CBDP programmes may not be difficult as the community is aware of it, but implementation of warning system would be more challenging. The system is new to both the implementing authorities and the communities who have to response to the warning. I recommend first to carry out feasibility study of the warning system both in terms of its implementation and the response. This will help in organizing the operational structure of the warning system.

9.6 Highlights of the research

This research provided the first published work in India, in the form of scientific publications, on quantitative estimation of landslide hazard and risk, as evident from the report of NDMA (2009). According to the report “landslide risk zonation has so far not been attempted in India” (NDMA, 2009, page 76). This research is among the few landslide works being undertaken in the Nilgiri area with the assistance of the local authorities with an aim to find out feasible solution to the landslide problem. This will help in understanding the requirements for quantitative assessment of landslide risk along transportation corridors.

Some of the main highlights of the research are:
1. The research demonstrated the possibility of obtaining a multi-temporal landslide inventory with known dates of landsliding using historical data
sources that are cost-effective and substantially complete. This approach of inventory mapping will be of immense value particularly in developing countries where landslide losses are high yet other sources of extracting landslide information, such as remote sensing data of multiple dates, image processing software, high precision stereoscopes, etc., are not available.

2. The research demonstrated that rainfall thresholds for landsliding are dynamic and vary with changes in the local terrain conditions even within the small study area. Therefore, a regionally-derived threshold may not be suitable for developing a warning system and forecasting landsliding at a local scale.

3. The research demonstrated that the probability density of landslide volume exhibits a negative power law distribution either for all ranges of volumes or for landslides exceeding a certain threshold volume. Thus, the roll-over observed for small landslides in some cases is ‘real’ and not an ‘artefact’ due to sampling discrepancies. The research showed the importance of landslide volume-dependency on the intensity of rainfall and local terrain condition, at least for those initiating on cut slopes.

4. The research presented a direct method of landslide hazard analysis for repetitive slope failures along transportation lines and an indirect method, based on rainfall thresholds, for rainfall induced slope failures on natural slopes.

5. The research presented an approach to quantify risk in a data scarce situation using a limited inventory on natural slopes and by assessing the key information from a more complete inventory on landslides in untreated excavated slopes along roads and railroads.

6. The research presented the perception of the Nilgiri communities to landslide risk and a model for a warning system of landslide forecasts for the first time in India.

9.7 Scope for future research

Based on the outcomes of this research and considering the stage of development of landslide risk research, the following future work in continuation of this research is suggested:

1. Further development is needed on the possibility of incorporating run-out zones and debris flow inundation areas in a quantitative landslide probability map using GIS for the optimal assessment of risk.

2. Future research should focus on development of a better temporal model, which can forecast landslides more accurately and with less uncertainty.
3. Specific research is needed for the assessment of vulnerability of different elements at risk (movable and stationary) due to landslides of different types, volume and velocity.

4. For this specific case study (Nilgiri area) and for India as whole, future research should focus on developing risk tolerance criteria.

The study demonstrated the importance of historical information in landslide hazard and risk analysis. It is rightly pointed out by researchers like Glade (2001) that "landslide hazard assessment and historical landslide data is an inseparable couple".
References


References


References


References


References


Finlay P.J., 1996. The risk assessment of slopes. School of Civil Engineering, University of New South Wales, Australia, PhD thesis.


References


References


References


References
Biography

Passionate commitment, strong self-motivation and adapt to change

Pankaj Jaiswal was born on the 15th of June 1976 in Hazaribag, Jharkhand, India. In 1998, he obtained his M.Sc. degree in Geology from University of Delhi (India). After M.Sc. he joined Geological Survey of India, Lucknow, Uttar Pradesh as a Junior Geologist. From 2001 to 2006 he worked under different projects of Geological Survey of India, including landslide susceptibility mapping of Yamuna and Ramganga river basin at a catchment scale, and landslide susceptibility mapping along transportation corridors in the higher Himalayan terrain covering parts of Kailash - Mansarover pilgrim road corridor up to Indo-China border. The project reports are available in www.portal.gsi.gov.in. In 2007 he was promoted to Senior Geologist. From 2007 to 2011 he worked on his Ph.D. research under sandwich programme in collaboration with Geological Survey of India (GSI), National Remote Sensing Centre (NRSC) in India and Faculty of Geo-information Science and Earth Observation (ITC), University of Twente in The Netherlands. His research focuses on the quantitative estimation of landslide risk along transportation corridors using information derived from historical records, which eventually resulted in this thesis. He has published scientific articles in journals and conference proceedings. His future research interest is to work on different applications of quantitative risk models in developing strategies for risk reduction.
Publications related to this research


Samenvatting

Aardverschuivingen zijn een veel voorkomend probleem langs verkeersinfrastructuur in bergachtige gebieden. Ze veroorzaken niet alleen materiële schade aan eigendommen (weg en spoortracés, gebouwen, voertuigen, enz.) en doden en gewonden, maar ze hebben ook een negatieve impact op de maatschappij door de onderbreking van economischeactiviteiten. Om deze negatieve effecten te verminderen is het noodzakelijk om het risico van potentiële aardverschuivingen kwantitatief te schatten, en een kostenbaten analyse voor mogelijke maatregelen voor risicovermindering uit te voeren.

Voor de analyse van het risico van aardverschuivingen is het essentieel om informatie te hebben waar en wanneer deze in het verleden opgetreden zijn en de gerelateerde verliezen. De beschikbaarheid van een volledige inventarisatie van massabewegingen over een langere periode is daarom van het grootste belang. Helaas zijn de meeste inventarisaties die gemaakt worden op basis van satellietbeelden, luchtfoto’s, veldwerk, en archieven zelden volledig.

Volledige inventarisaties kunnen slechts voor specifieke gevallen gereconstrueerd worden, bijvoorbeeld in situaties waarbij aardverschuivingen langs de taluds van wegen of spoorwegen over een lange tijd geregistreerd worden in een kadaster dat voor onderhoudsdoeleinden wordt gebruikt. Dit onderzoek maakte gebruik van dergelijke gegevens voor het genereren van een database van massabewegingen waarin vrijwel alle fenomenen geregistreerd zijn die over een periode van 21 jaar zijn opgetreden. Dit onderzoek presenteert een methode om deze te gebruiken voor het kwantificeren van aardverschuivingsgevaar en risico langs (spoor)wegtracés en deze resultaten vervolgens te gebruiken voor de omringende natuurlijke terreinheilingen, waarvoor veel minder historische gegevens beschikbaar zijn. De historische gegevens werden gebruikt in de analyse van kritische drempelwaardes voor regenval, die de basis vormden voor de identificatie van gevaar van hellingsinstabiliteit op natuurlijke hellingen en voor de ontwikkeling van een lokaal waarschuwingssysteem voor massabewegingen.

ondiepe vlakke afglijdingen en modderstromen ontstaan ten gevolge van hevige regenval. Diverse analyses werden uitgevoerd om het risico langs de weg, de spoorweg en de omringende gebieden te kwantificeren. Een Gumbel analyse werd uitgevoerd om de frequentie van aardverschuivingen op taluds en op natuurlijke hellingen te bepalen. Een multivariate statistische methode werd uitgevoerd om de gevoelige gebieden voor massabewegingen op natuurlijke hellingen te modelleren. De kritische drempelwaarde van regenval werd gebruikt om de temporele waarschijnlijkheid te bepalen en een analyse van de frequentie en grootte werd uitgevoerd om de waarschijnlijkheid van bepaalde volumes van massabewegingen te schatten.Deze gegevens werden gecombineerd in een analyse van het gevaar voor het ontstaan van massabewegingen langs taluds en op natuurlijke hellingen. Een analyse van de hellingsafwaartse beweging van massabewegingen werd uitgevoerd voor de natuurlijke hellingen op basis van de gemoduleerde initiatie gebieden en te verwachten volumes. De kwetsbaarheid voor schade werd bepaald voor verschillende elementen, zoals de rijbaan en spoorwegrails, bruggen en andere civiele werken langs de verkeersinfrastructuur, gebouwen, voertuigen en personen. De risicoanalyse werd gedaan op basis van aardverschuivingen die in de periode tussen 1987 en 2007 optraden en een validatie werd uitgevoerd met massabewegingen die in 2008 en 2009 plaats vonden. De analyse betrof zowel het directe risico voor fysieke objecten (tracés, voertuigen, gebouwen, en gewassen) en mensen (forenzen en lokale bevolking) evenals de indirecte risico’s welke veroorzaakt werden door de onderbreking van het verkeer langs de weg en de spoorlijn. De resultaten van het onderzoek werden vergeleken met de risicoperceptie van de lokale bevolking, en een aantal voorbeelden werden uitgewerkt om de resultaten te gebruiken in het ontwerpen van maatregelingen voor risicovermindering.

De resultaten resulteerden in een kwantitatieve raming van de totale te verwachten jaarlijkse verliezen, uitgedrukt in monetaire waarde (US$) alsmede van de jaarlijkse waarschijnlijkheid van slachtoffers. Een zogenaamde F-N curve werd gebruikt om de bevolkingsrisico’s uit te drukken. De resultaten hebben een belangrijke sociale waarde en vormen de basis voor de planning van strategieën voor risicovermindering, voor het ontwikkelen van criteria voor acceptabele risico’s en voor financiële analyse voor mogelijke schade in het studiegebied. De ontwikkelde methode vormt een toepasbare benadering voor de kwantitatieve bepaling van directe en indirecte risico’s voor aardverschuivingen, die ook kan worden toegepast in andere gebieden met vergelijkbare problemen, mits er voldoende historische gegevens over massabewegingen beschikbaar zijn.
ITC Dissertation List

http://www.itc.nl/Pub/research_programme/Graduate-programme/Graduate-programme-PhD_Graduates.html