Factors Affecting Risk from Natural Hazards, Kullu Valley, Himachal Pradesh, India

by

Eric A. Saczuk

A Thesis Submitted to the Faculty of Graduate Studies of

The University of Manitoba

in partial fulfillment of the requirements for the degree of

Doctor of Philosophy

Department of Environment and Geography

University of Manitoba

Winnipeg

THE UNIVERSITY OF MANITOBA

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Abstract

Natural hazards are natural phenomena that produce net negative effects on people and their livelihoods and may include processes of flooding, landslides, debris flows and rock fall. Mountain regions are particularly susceptible to the occurrence of natural hazards owing to the frequent juxtaposition of human-built infrastructure with the release, transport or deposition zones of natural erosion processes. The Kullu Valley served as the study area for a comprehensive examination of the effects of changes in land use/cover, climate and seismic activity on the exposure of people and their livelihoods to risk posed by natural hazard processes between 1972 and 1999. Through field work, GIS-based land use/cover change and run-out zone modeling, a review of current literature and historical data, an examination of a 98-year climate record and 122-year seismic record, and interviews with local inhabitants it was established that land use/cover change in the deposition/inundation zones accounts for most of the apparent increase in risk due to natural hazard between 1972 and 1999.

Further analysis found little evidence to support the theory that much of the Himalaya is undergoing rapid deforestation leading to noticeable changes in the frequency and magnitude of slope erosion and denudation processes. Forest cover, climate and earthquake activity, the main factors influencing the material activity of slope processes and floods, have not changed appreciably in the study area over the past century.

The intended globally-applicable nature of the techniques developed and used here requires more research be carried out in order to validate the deposition model with data

from other mountain areas. The GIS-based framework provides a convenient and flexible approach to the cataloguing and analysis of any spatially referenced data related to the occurrence, activity and change of natural hazards in any mountain area.

Acknowledgements

The author would first like to thank those who were directly responsible for making this thesis a reality; Dr. James Gardner who by literally taking me into the mountains, showed me firsthand the complex and beautiful nature of these landscapes and the people who inhabit them; Dr. David Barber who despite a million better things to do guided me along the way and saw to it that I didn't stray too far off the remote-sensing path; Dr. Michael Campbell who more than once lent a seasoned ear and offered invaluable advice on the finer points of fluvial geomorphology; and last but certainly not least, Dr. Jim Teller who subtly encouraged me not to cut corners and patiently put up with far too much mediocrity from me.

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At one time or another Kristen Bingeman, Gillian Chilibeck, Maira McDermot, Laura Sparling and Mehru Thakur all somehow ended up on the back of the motorcycle with the backpack full of gear heading up to Rohtang Pass. You not only made my stay in India infinitely more enjoyable and memorable, each of you also helped me out in different ways and for that I am indebted.

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1) Schematic views of Indian tectonics, Earthquakes in India and the Himalaya: tectonics, geodesy and history by Roger Bilham, 2004, *Annals of Geophysics*, 42(2), 839-858. Page 82.

Chapter 1 Introduction and Literature Review

1.0 Introduction and Purpose

All anthropogenic activity on the Earth's surface is superimposed onto an evolving physical landscape that is continuously being reshaped by endogenic forces of uplift and exogenic processes of erosion and denudation. The spatial and temporal intensity and frequency of these processes are magnified in mountainous regions compared with lower relief areas. The physical factors driving endogenic and exogenic forces such as tectonics, relief, slope angle, and aspect among others are all amplified in mountain regions. The transport of material from higher to lower elevations and its subsequent deposition on gentler slopes near the valley bottom coincides with the preferred location of human settlements and infrastructure in mountain areas (Figure 1.1).

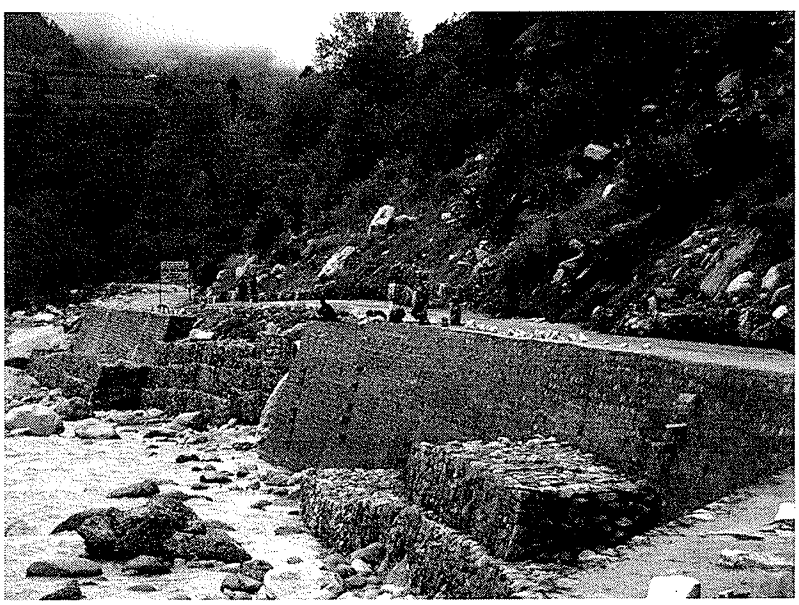


Figure 1.1 An example of the juxtaposition of infrastructure onto slopes affected by landslides, floods and bank erosion in the Kullu Valley. (Author, July 1999)

This geographical juxtaposition of human and geomorphic activity results in a condition of natural hazard which exposes people and structures to a certain level of risk posed by the particular erosion and denudation processes operating in an area. As a result, landslide-related losses are significant in many mountain areas. Naithani *et al.* (2001) reports that damage caused by landslides in the Himalaya amounts to more than 1 billion U.S. dollars, and they are responsible for over 200 deaths per year. Worldwide "…economic losses due to landslides are estimated to be in the order of two to five billion US dollars" each year (Schuster, 1994 *in* Temesgen *et al.*, 2001, p. 665).

It is not surprising then that scientific, academic, and popular interest in the increasingly complex interactions between people and mountain landscapes has risen dramatically over the past several decades, leading to the emergence of a wide variety of theories on the causes and effects of people on the environment and of the environment on people in the Himalaya. Some researchers have warned of the impending, unavoidable, and complete deforestation of the Himalaya (e.g. Myers, 1986; Karan and Iijima, 1985; World Bank, 1979; Rieger *et al.*, 1976; Sterling, 1976; Eckholm, 1975), while others discount human activity as having a negligible impact on the evolution of the physical landscape compared with natural processes (Hofer, 1993; Messerli, 1992; Ives and Messerli, 1989; Hamilton, 1987; Thompson and Warburton, 1985). One of the main problems and perhaps the overriding reason for such disparate viewpoints is the general lack of reliable empirical data for the whole region from which to draw any all-encompassing conclusions about the relationships between people and the complex physical landscape of the entire Himalayan mountain range (Hofer, 1993; Lauterburg, 1993; Thompson and Warburton, 1985). Most often study sites are large- or meso-scale (i.e. < 1,000 km^2), constrained by inaccessibility, the logistics of carrying out research in the rugged and remote valleys, and the cultural and physical heterogeneity of the Himalaya. There are a few exceptions, namely the works of Zurick and Karan (1999) and, to a lesser degree, Ives and Messerli (1989) who have invested considerable time living in and studying many of the diverse aspects of both the physical and human landscapes of much of the Himalaya. There is little doubt that the consequences of increased land pressures are causing land degradation in certain parts of the Himalaya but care must be taken not to generalize this to the entire region. Micro- and meso-scale differences in climate, geology, vegetation and human land use all play a role in determining the extent to which human activities affect natural processes of denudation and vise versa.

The construction of a highway may lead to pronounced slope instability in one region whereas in another, the effects may be insignificant due to subtle differences in climate, geology, topography, land management practices and many other disparate factors. Policies and regulations pertaining to the construction of roads or terraces, for example, differ between India and Nepal resulting in differences in slope stability under similar physical conditions. What becomes evident is that the Himalaya are physically and culturally diverse and thus deserve to be studied in a manner that takes the scale of this diversity into account.

One of the many areas that continues to experience land use/cover change as a result of population growth and urban development is the Kullu Valley in northern Himachal Pradesh, India, where this research was conducted (Figure 1.2).

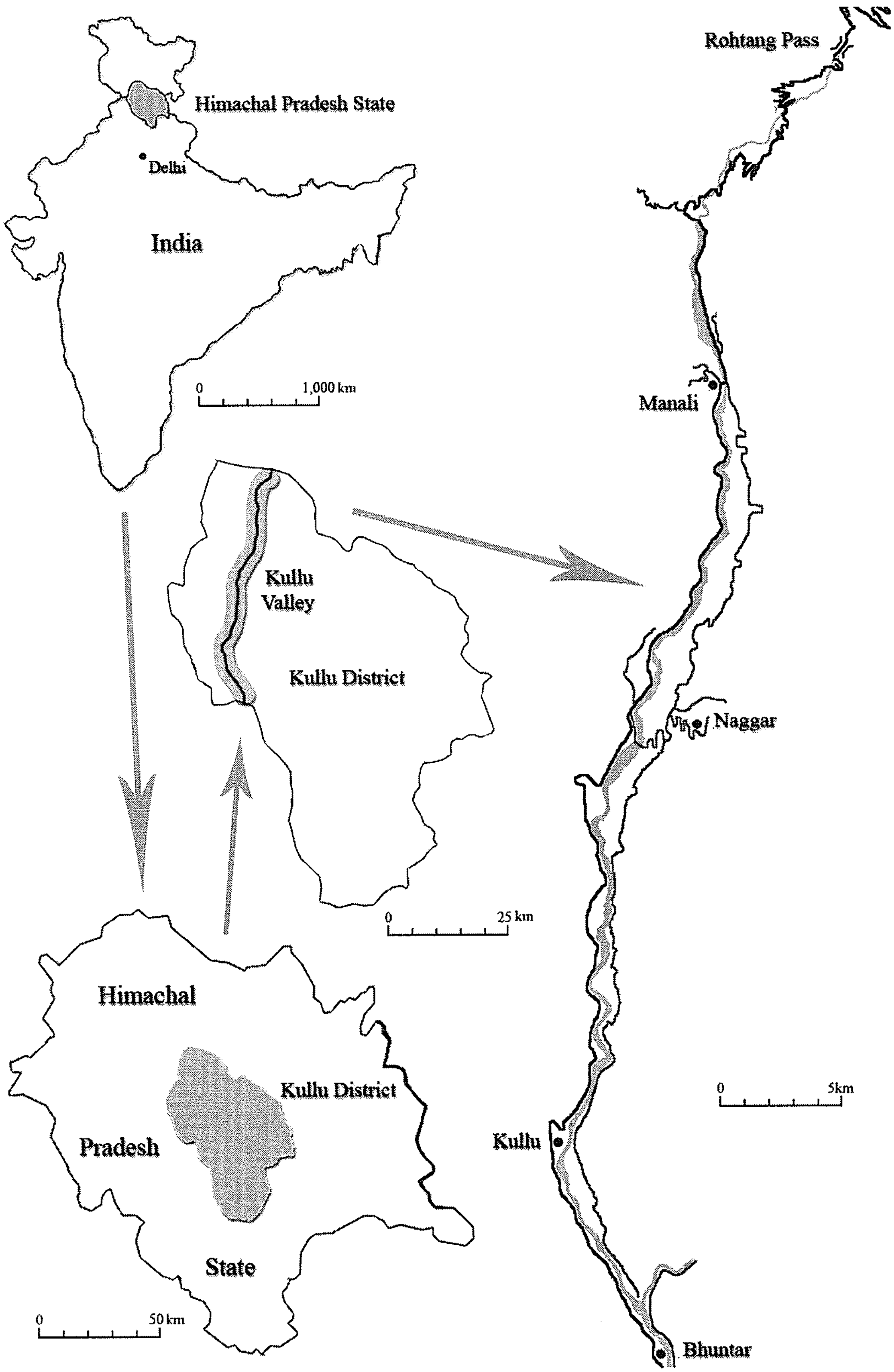


Figure 1.2 Study area in the upper Kullu Valley, Himachal Pradesh, India. (Modified from MapsofIndia.com © 2006 and Author)

The Kullu Valley, similar to all mountain areas, is subject to natural processes of denudation including landslides, rock falls, debris flows, floods, and avalanche activity. The effects of these processes on people and infrastructure in certain localized parts of the valley have been studied by Gardner (2002), Sah and Mazari (1998), Gardner *et al* (1997), Gupta (1997), Rao (1997), Yudhbir (1997), and Singh and Pandey (1995) among others. Gardner *et al.* (1997) and Kuster (1993) assessed the effects of deforestation on the state of natural hazards near Manali, the main tourist centre in the Kullu Valley, and concluded that;

> "There is relatively little evidence (to suggest) that human activities have materially altered the frequency, magnitude, and location of hazardous processes so as to increase risk except in a few, very localized situations. The primary causative factors in the increased risk are growth in tourist demand and intensification and diversification of commercial agriculture." (Gardner *et al.,* 1997, p. 251).

This concept is advanced here by addressing the question of how the spatial pattern of exposure of people and infrastructure to natural processes of denudation has changed as a result of changes in land use/cover, climate and seismicity along the main transportation corridors in the Kullu Valley over the past several decades. The results are intended to close several knowledge gaps that have been identified in current natural hazards research. Firstly, on a local scale, human development in the Kullu Valley continues to expand and intensify, thus necessitating a systematic examination of how these land use/cover changes are affecting the exposure of people and associated infrastructure to processes of active mass wasting and denudation presently and in the future. Secondly, this research addresses the need to collect more reliable empirical data in a systematic and scientific manner in order to better understand the changes occurring in the mountains of Himalaya. Thirdly, the study site is used as a test case for the development of methods with which to assess the exposure of particular cultural elements of interest to natural processes of denudation as a result of changes in land use/cover, climate and seismicity using geographic information systems (GIS).

1.1 Hypothesis and Objectives

It is hypothesized that the recent and ongoing expansion and intensification of infrastructure, which began in the early 1970's in the Kullu Valley, is increasing the susceptibility and thus risk of people and property to natural hazards posed by processes of denudation and flooding along the main road network adjacent to the Beas River in this region of the northwestern Himalaya. The hypothesis is tested by addressing the specific objectives listed below:

1) Identify, locate, document, map and model sites of known and potential slope instability and inundation adjacent to the main network of roads along the Beas River.
2) Identify the pattern of land use/cover change for areas in close proximity to the Beas River and for sites affected by erosion and flooding processes between 1972 and 1999.
3) Estimate how changes in land use/cover, climatic factors and seismic activity have altered the susceptibility of people and infrastructure to natural hazards in the Kullu Valley.

1.2 Previous Research

A comprehensive review of the pertinent literature related to hazards in the Himalaya is presented below. The section begins with a discussion about the role of scale in hazards research for the Himalayan region as a whole, individual ranges as well as specific slopes. This is followed by an examination of the main factors affecting and driving natural hazard processes including tectonics, bedrock and surficial geology, weather and climate, geomorphology and its history, and the effects of human impacts through land use/cover change. The final subsection categorizes and reviews the current literature according to the main themes or approaches used in hazards research including geomorphic, hazards-specific, hazards mapping, and human impact studies.

1.2.1 Scale

This research builds on the efforts of previous authors who have carried out studies in the Himalaya and the Kullu Valley region. Much of the work on mass wasting, erosion, denudation and hazards identification and mapping has focused on small study sites in the central and eastern Himalaya, particularly Nepal and the Garhwal and Kamaun regions in the western mountains. Several authors have attempted to characterize the full scope of the physical environment of the whole Himalayan region through their own research, a review of available literature, or a combination of both. A comprehensive review of much of the influential literature on mass wasting processes in the Himalaya over the past century is provided by Shroder Jr. and Bishop (1998) who categorized the scale of processes into those affecting entire mountain ranges, individual mountains and portions of slopes. This scale-dependent approach is an extension of the main forces that drive each of the processes. Gravity-driven tectonics affect large regions, factors controlling rock strength directly modify the morphology of mountain peaks, and slope angle and land use/cover govern the processes operating at large scales on individual slopes or portions of slopes.

The main focus of this research is on changes occurring on individual slopes along a 120 km-long section of the upper Beas River watershed, from its headwaters at Rohtang Pass to just south of Kullu where the river exits the Kullu Valley through a narrow gorge to the west. Although the relative remoteness and inaccessibility of the Himalaya are cited by Shroder Jr. and Bishop (1998) as the main reasons for the general lack of research and consequently reliable data in the area compared with other mountain areas, they recognize that recent developments in GIS technology, remote sensing, and geomorphometry are helping to bridge this information gap and strengthen our understanding of the geomorphological processes operating in the area.

1.2.1.1 Himalayan Region

Several examples of hazard-related research that attempt to encompass the entire Himalayan mountain range can be found in previous literature, with the theory of Himalayan degradation as labeled by Ives and Messerli (1989) the most known and perhaps notorious. Eckholm (1976, 1975) alleged that the rapid and rampant erosion in the hills and subsequent flooding in the plains is a direct consequence of the irresponsible land management practices carried out by indigenous farmers living throughout the Himalaya. Since the introduction of this argument, a number of authors including Thapa and Weber (1990), Myers (1986), Reiger (1981), and Sterling (1976) have directly or indirectly expressed their support for the idea that anthropogenic activities such as cultivation, terrace construction and deforestation have materially increased the frequency and magnitude of natural erosion processes throughout the Himalayan region. Other authors including Hofer (1993), Metz (1991), Hamilton (1987), Byers (1986), Ramsay (1986), and Carson (1985) perceived this as a direct attack on the Himalayan farmer and challenged the validity of some of the conclusions claiming that there is simply not enough empirical evidence to draw such direct and all-encompassing conclusions regarding the relationship between the volume of sediment eroded from Himalayan mountains and the role of the indigenous farmer. The publication by Ives and Messerli (1989) in particular has had a profound effect on public perception and, perhaps more importantly, the national and international funding agencies, of what was and is actually happening in the Himalaya for a number of reasons (Fisher, 1990). Ives and Messerli (1989) coined the term "Theory of Himalayan degradation" (subsequently referred to here as the Theory) mainly in an attempt to synthesize all or most of the ideas, theses and arguments which supported the initial research carried out by Eckholm (1976, 1975) but also partly to artificially strengthen the opposing argument in order to subsequently attack and dismantle it. Despite the validity of many of the arguments put forth by the authors regarding the general notion that there is simply not enough reliable evidence to support the idea that the Himalaya are uncontrollably mass wasting into the ocean at the hands of the people who have inhabited the region longer than anyone else, other authors have also sensed that Ives and Messerli seemed too focused on repeatedly trying to debunk the Theory which they themselves created. The main drawback to the Theory is that Ives and Messerli (1989) pay too little attention to other important issues, including the value of forests as wildlife habitats and the fact that it was local people (e.g. Chipko movement) who first recognized the potential negative consequences of deforestation on the landscape and their livelihoods (Rawat, 2004). Most scholars, researchers and stakeholders now realize and appreciate the incredible complexity and intricacy of the Himalayan environment both in the physical and cultural sense and are conscious of the dangers associated with extrapolating and generalizing results gained from one small area in the Himalaya to other larger areas.

Zurick and Karan (1999) appear to have grasped the inherent complexity of the region and offer a well-balanced summary of many of the issues, including natural hazards, facing the people who live in the Himalaya now or have lived there in the past. Although the work of Zurick and Karan (1999) goes well beyond a simple review of the history of deforestation, land management practices and the links between them and erosion processes, one of the common themes between their work and the work of Ives and Messerli (1989) is the recognition of the lack of accurate and reliable empirical data for many areas of the Himalaya. Shroder Jr. and Bishop (1998) offer one of the few examples of a comprehensive assessment of the current state of hazards for the entire Himalayan mountain range. Beginning with a discussion about the relationships between uplift and denudation and the altudinal, linear and temporal distribution of various gravity-driven degradation processes, the authors proceed with a thorough region-based literature review, discuss the concept of maximum size of stable hillslopes, present new developments in assessment of mass movement, and conclude that surficial geomorphic processes may be as important as lithospherically-controlled tectonic unroofing in denudation of the Himalaya. Shroder Jr. (1998), focusing on a small portion of the Western Himalaya, reviews the geologic history of Himalayan denudation through a detailed analysis of a number of recent and historic failures. He also briefly discusses the relation of mass movements to glaciation and the role of catastrophic floods in debris entrainment and denudation, and concludes by calling attention to the lack of research on denudation estimates by shallow erosion which are referred to as "...the major present-day process shaping the landscape" (Shorder Jr., 1998, p. 102).

Heimsath (2000) examines the general impacts of the extent and nature of vegetation removal, terrace agriculture and road construction across the Himalaya on erosional processes with a goal "...to review Himalayan erosion rates from a process-based perspective..." (Heimsath, 2000, p. 3). The author reviews previous literature to estimate the range of denudation rates associated with glaciers, periglacial processes, landslides, debris flows rock falls, soil creep and fluvial processes, and discusses the potential impacts of humans on erosion rates through changes in land use/cover. Heimsath (2000) concludes that although more detailed, valley- or slope-specific research would be needed to absolutely quantify denudation rates, results indicate that increased erosion rates due to human impacts are not "...enough to make a noticeable contribution to the already enormous sediment load being transported out of the Himalaya..." (Heimsath, 2000, p. 16).

The need to better quantify the denudation rate due to shallow erosion processes and to assess the impacts of anthropogenic activity on the slopes as manifested through land use/cover change is an underlying theme in the literature reviewed above. It is also evident that some valleys have received much attention (e.g. Khumbu Valley in Nepal and several valleys in the Garhwal Himalaya) while data for other areas with different geologies, climate, land use practices, and cultural and physical histories is still relatively scarce. As will be discussed further below, the impacts of human activity on the Himalaya landscape seem to be detectable only in localized areas and almost certainly do not appear to have wide-ranging consequences on the frequency and magnitude of mass wasting and flooding processes in the hills and by extension in the plains.

1.2.1.2 Individual Ranges or Regions

While the above examples broadly illustrate some of the region-wide research efforts and the complexity of the whole Himalayan range, it is also important to draw attention to studies that have considered a region of similar size to the Kullu Valley in order to identify the main approaches and problems associated with hazards research on this scale. Regional studies carried out in Nepal and India, including the Kullu Valley, are reviewed below.

Numerous regional-scale studies have been carried out in various parts of Nepal including Kulekhani watershed (Dhakal *et al.*, 1999), Sagarmatha National Park (Jordan 1994), Phewa Tal watershed (Rowbotham and Dudycha, 1998), Khumbu Himal (Vuichard, 1986), Manaslu-Ganesh and Langtang-Jugal Himals (Marston *et al.*, 1998), Marsyandi and Buri Gandaki drainages (Marston *et al.*, 1996), Dhankuta District, Koshi Hills (Virgo and Subba, 1994), Likhu Khola drainage basin (Gerrard and Gardner, 2002), Jhihku Khola watershed (Schreier *et al.*, 1990) and Roshi watershed (Gautam *et al.* (2001). Research in India has focused on the Nana Kosi watershed (Rawat and Rawat, 1994), the Kullu District (Gardner, 2002; Gardner *et al.*, 2002; Singh and Roy, 2002; Singh and Pandey, 1996), Kali Valley (Paul *et al., 2*000), Dehradun and Mussoorie (Panikkar and Subramanyan, 1996), Garhwal Himalaya (Vaidyanathan *et al.*, 2002; Barnard *et al., 2*001; Sarkar *et al.*, 1995; Nainwal *et al.*, 1985), Arunachal Pradesh (Kayal, 2001), Darjeeling (Froehlich and Starkel, 1993) and Bhagirathi (Ganga) Valley (Saha *et al.*, 2002) (Figure 1.3).

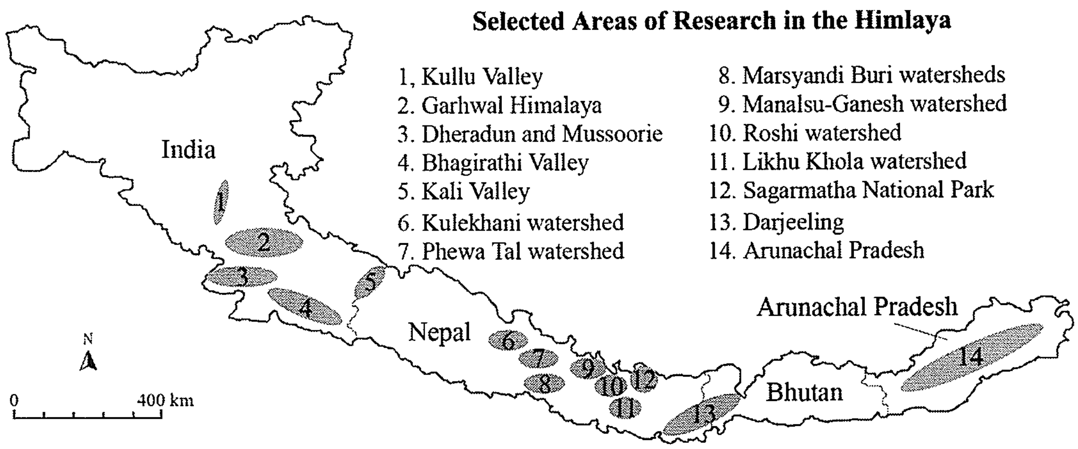


Figure 1.3 Location map showing the study area with respect to areas of previous regional-scale research. (Author)

The main approach to the analysis of hazards on a regional scale involves assessing the human impacts on the physical environment (Singh and Roy, 2002; Gerrard and Gardner, 2002; Gautam *et al.,* 2002; Singh and Pandey, 1996; Jordan, 1994; Rawat and Rawat, 1994; Virgo and Subba, 1994; Froehlich and Starkel, 1993), using factors such as land use/cover change (Gautam *et al.,* 2001; Marston *et al.*, 1998, 1996; Rowbotham and Dudycha, 1998; Singh and Pandey, 1996; Virgo and Subba, 1994). GIS is now frequently applied to the analysis of land use/cover change as it relates to hazards and the production of hazards (Dhakal *et al.*, 1999; Rowbotham and Dudycha, 1998) maps, while Gardner (2002) advocates an historical approach to the analysis of human activity and its effects on geomorphic processes and the landscape in terms of risk and susceptibility. Other important regional-scale approaches to hazard assessment rely on careful examination of geological factors, particularly tectonic and neotectonic activity and its role in predisposing slopes to instability and triggering mass movements (Barnard *et al.*, 2001; Kayal, 2001; Paul *et al.*, 2000; Panikkar and Subramanyan, 1996; Sarkar *et al.*, 1995). Some specific examples of regional-scale research in the Himalaya are discussed below.

Following a detailed study of the seismicity, geology and climate of the Kali Valley in Kumaun Himalaya, India, Paul *et al.* (2000) determined that a devastating earthquake-induced landslide, which killed 221 people and dammed a tributary stream, was caused by a combination of near vertical, overhanging slopes, the presence of structural wedges along the exposed face, the proximity of major tectonic planes, and an increase in pore-water pressure resulting from prolonged rain events in the days preceding the event. Panikkar and Subramanyan (1996), working in the Doon Valley of the Mussoorie Hills of northern India, evaluated the influence of various geomorphic, geologic, and anthropogenic parameters on the occurrence of 75 landslides identified by remote sensing. Their results indicate that rock and debris slides occur mainly in areas of quartzite and limestone lithology, in close proximity to active faults, on south-facing slopes with gradients between 18° – 45°, where the removal of supporting material by stream undercutting is exacerbated by a deforested land cover and most often triggered by rainfall and earthquake activity. According to research carried out by Suneja (1977) in western Himachal Pradesh state, landslides in the Kangra District are mainly found along road cuts in highly fractured Tertiary beds composed of alternating sequences of fine-grained clays interbedded with sandy, coarser sediments, and result in significant losses of life, property, natural vegetation, and fertile soils. Diminishing vegetation cover due to over-grazing of cattle on the upper slopes and the continuous undercutting of toe material by streams and gullies are further exacerbating slope instability (Suneja, 1977). Hazards research by Singh and Pandey (1996) in the upper Beas River basin in Himachal Pradesh, identified the influx of tourists and the development of related infrastructure and a change in the local land tenure act in the late 1960's as the main causes of the increase in mass wasting and landslide activity in the late 1990's. The authors correlate the activity of about 50 active landslides along a 52 km stretch of National Highway 23, which links Manali with Leh, to proximity to fault lines and the construction of the road over weak unconsolidated deposits and morainal materials for much of its length. Barnard *et al.* (2001) blame the recent (i.e. last several decades) increase in human activity for the occurrence of over two thirds of 338 shallow, earthquake-induced landslides identified in a 226 km^2 area of the Garhwal Himalaya. Specifically, the authors identify the removal of toe material from slopes for the purpose of road construction as the main destabilizing factor, however, they also concede that "...the precise contribution of human activities to regional denudation cannot be quantified" (Barnard *et al.*, 2001, p. 34) and call for care in the extrapolation of results from small study areas to larger regions due to the physical diversity of the region.

Tolia *et al.* (1997) investigated a slope failure near Kullu town that killed 22 people and completely destroyed the left-bank road linking Kullu with population centers further north including the main tourist destinations, Manali and Rohtang Pass. According to the authors this slope failure was caused by flooding of the Beas River which undercut the supporting toe material and oversaturation of the slope due to heavy rains. This disaster "...brought the attention of planners and the construction engineers toward the lack of proper planning before the construction of the road." (Tolia *et al.*, 1997, p. 95). Although the alignment of the road at this site (adjacent to the river and at the base of the steep, unconsolidated slope) likely contributed to the failure, the main destabilizing force was most certainly the very large flood which occurred several days prior to the failure (September 5th and 6th, 1995). Sah and Mazari (1998), focusing on the same landslide site as described by Tolia *et al.* (1997), take a more regional view and consider the factors and processes responsible for triggering widespread mass movement caused by the large flood and intense rain events of September 3rd through 6th throughout the Kullu Valley. According to the authors, mass movements in the Kullu Valley have increased both in frequency and intensity since the 1950's mainly due "...to escalating socio-economic development, growth of tourism, and population pressure" (Sah and Mazari, 1998, p. 123). Sah and Mazari (1998) call for a review of current hazard policy and urban planning strategies in order to mitigate against future such events while minimizing damage to the natural environment.

Gupta (1997) presents a comprehensive inventory of hazards affecting roads for much of the Himalaya but pays particular attention to the damage caused by landslides and flooding to National Highway 21 (NH 21), the main transportation corridor along the

Beas River in the Kullu Valley. Some 100 sites of active slope activity were identified within a 40 km stretch by the author who stresses that these slope processes also adversely affect agricultural fields, orchards, forest land, hotels, and tourist-related infrastructure. Some of the recommendations offered by Gupta (1997) to reduce the risk from natural hazards include; increased awareness of hazards in affected areas and; develop a global database for the technological advancement of natural hazard mitigation and management techniques that is accessible to all countries.

According to Gardner *et al.* (1997) risk from natural hazard in the area of Manali in the Kullu Valley primarily derive from floods, torrents, slope failures, snow avalanches, and earthquakes. According to the authors, "...there is no evidence that frequency and magnitude of such processes, and therefore risk, has increased as a consequence of forest degradation..." (Gardner *et al.*, 1997, p. 237). However, through a detailed review of historic literature, interviews with long-term residents and field work, Gardner *et al.* (2002) and Gardner *et al.* (1997), demonstrate that the exposure of people to the risk posed by these natural processes has increased, especially over the past 25 years, mainly due to the development of tourism-related infrastructure and continued urbanization and concentration of people in certain locations in the valley.

An extensive review of historical forest cover changes in the Himalaya, using a specific case study in the Kaghan Valley of northern Pakistan, led Schickhoff (1995) to conclude that much of the deforestation in the Himalaya occurred during the first two decades of British rule (1847 – 1867). The increasing pressure on forest resources in many Himalayan valleys often leads to gradual, negative changes in stand structure rather than quantitative losses of forest cover, however Schickhoff (1995) clearly states that results from one study area are rarely applicable to other regions lagerly due to differences in the accessibility of an area dictated primarily by relief. The author contends that the results gained in the Kaghan Valley can only be transferred to other regions if the relief, accessibility, road infrastructure, historical pattern of change in socioeconomic conditions, and patterns of forest ownership are similar to those of the study area. Rawat and Rawat (1994) highlight the need for detailed, site-specific process studies by carrying out a two-year investigation of the human impacts on the monthly, seasonal, and annual stream runoff characteristics of the 55 km^2 Nana Kosi watershed in the Indian Kumaun Himalaya. In terms of water input into the channels from the land, the authors found that runoff from disturbed agricultural land was twice as high as from forested areas in the rainiest month (July), while during the driest and hottest month (April) the situation reversed and oak and pine forests were found to contribute 1.7 times the runoff measured on disturbed slopes. Furthermore, Rawat and Rawat (1994) report that while the most disturbed agricultural land yields more than 60% of the monthly runoff in July, on an annual scale, forested areas yielded twice as much runoff as agricultural areas mainly due to higher evapotranspiration rates in degraded areas which translates into a 50% reduction in annual runoff due to deforestation in the study area.

Examples of landslide hazard zonation in the vicinity of the Kullu Valley are provided by Saha *et al.* (2002) and Sarkar *et al.* (1995). Focusing on a tectonically-active 600 km^2 area near Srinagar-Rudraprayag in Garhwal Himalaya, Sarkar *et al.* (1995) identified and classified hazard-prone areas based on weighted maps of slope angle, lithology, distance from major geological discontinuities, land use, drainage, relative relief, and existing landslides. Results of this regional study show that high landslide densities (>31 / km^2) are associated with close proximity to the North Almora Thurst zone, Pauri Phyllites, 15° – 25° slopes, barren land use, 400 – 500 m of relative relief, and low drainage densities (<2 km / km^2).

Saha *et al.* (2002) used satellite remote sensing data, topographic and geological maps, and field observations of 53 slope failure sites to generate GIS raster layers of land use/cover, buffer map of thrusts, buffer map of lineaments, lithology, buffer map of drainage, slope angle, and relative relief in order to produce a landslide hazard zonation map. The relative importance of each GIS layer was subjectively ranked and the individual categories within each layer were qualitatively assigned a weighting value with the highest weight assigned to each of the following categories; <500 m to thrust fault; Higher Himalayan Crystallines; barren land use/cover; <500 m to photo-lineaments; slope angles >45°; relative relief >120 m; and <50 m to drainage courses. Following the multiplication of the categories by the respective rank, the layers were added together to produce a hazard zonation map which was subsequently reclassified into five hazard categories. By overlaying a map of actual landslides identified in the field onto the hazard zonation map, the authors found that relative to their area the two zones identified as most hazardous contained disproportionately more landslides than the other zones, validating the subjectively assigned ranks and weights. Saha *et al.* (2002) concluded that proximity to thrust zones, crystalline lithology, and barren or less-vegetated areas were most closely associated with known landslide sites.

Rowbotham and Dudycha (1998) applied GIS-based slope stability modeling techniques to the prediction of areas susceptible to landsliding in Phewa Tal watershed, Nepal. Although the authors employ a novel approach based on geomorphometric terrain units which offer several advantages over the more traditional pixel-based techniques, their methods and results are seriously hampered by heavy reliance on subjective decision rules and assumptions about knowledge of *a priori* stability conditions of an area by the researchers. Their attempt to model the distribution of slope stability for the Phewa Tal watershed was statistically successful indicating that most slope failures are closely associated with cultivated dipslopes, however the high level of subjectivity of these methods degrades their applicability to other areas.

A regional scale approach to hazard analysis provides pertinent information on the general status of slope stability, flooding and bank erosion for areas up to several hundred squared kilometers in size. The resulting hazards maps may serve as direct input into local land management policy or for land use planning by interested stakeholders. One of the main problems at this scale of analysis is that while detailed fieldwork is generally far too costly both in terms of time and money to carry out, and access to timely air photos for proper analysis and interpretation cannot always be guaranteed, the growing reliance on satellite-borne remote sensing imagery also presents limitations relating to resolution and scale as well as timeliness and cost. The need to perform ground validation of information derived from satellite imagery has also been identified as a challenge which can only be slowly overcome by continued data collection and validation in various mountain environments.

1.2.1.3 Individual Slopes

Hazard assessment of individual slopes is typically carried out for the explicit purpose of stabilizing or mitigating the risk posed by a particular hazard through engineering means. This scale of analysis allows for a much more detailed evaluation of particular forces operating within and on the slope using rather different techniques than those applied to the analysis of smaller-scale slope stability problems. Investigations of individual slopes allows for the calculation of the factor of safety, which is a quantifiable measure of slope stability based on values generated by piezometers, tensiometers and the results of soil strength tests among other factors (Deoja *et al.*, 1991). Certain factors gain importance over others in terms of their influence on slope stability and the potential for failure at this larger scale. For example, much more attention is paid to the effects of runoff, infiltration, ground flow and seepage (e.g. Brunsden, 1999) than geological factors which tend to be more homogenous over the smaller areas under investigation. Measuring, modeling and monitoring the movement of ground water and its effects on the resisting and driving forces within the slope constitutes one of the most popular approaches to stability analysis at this scale (Wu *et al.,* 2000). Mechanics-based 3-D models, some of which also take into account the temporal dimension, have been applied to individual slopes in order to predict the possibility of future failures based on input factors such as soil density, internal friction angle, hydrostatic pressure, land use/cover as well as climatic variables and horizontal ground accelerations due to earthquake activity (Pascual, 2001; Smadja, 1992).

Messerli *et al.* (1993) have edited a comprehensive collection of regional and large-scale research carried out in Nepal, while Deoja *et al.* (1991) provide specific risk engineering examples from the Hindu Kush-Himalaya. Tolia *et al.* (1997) and Sah and Mazari (1998) focus on a specific slope in the Kullu Valley, and Pascual (2001) and Smadja (1992) provide reference to individual slope hazard analysis from Dhunche and Salme, respectively, in Nepal. Some specific examples of detailed slope investigations are provided below.

Haigh *et al.* (1993) carried out detailed slope analysis on short sections of roads in the Lesser Himalaya of Uttar Pradesh known to be affected by rock fall, slumping and debris flow activity. Following abnormally high rain intensities associated with the 1978 monsoon, the researchers set out to measure a number of key parameters at several hundred sites with the aim of identifying which parameters could be used to estimate runout volume using remote sensing imagery or air photos. Using a tape measure, abney level and clinometer, Haigh *et al.* (1993) recorded over 20 variables at each site ranging from site dimensions, percent and type of vegetation cover to rock strength indices and following analysis found that both length and width of a landslide release scar could be used to accurately predict runout volume ($r = 0.76$ to 0.90). Since both width and length of a landslide scar are often measurable from air photos or high resolution satellite imagery, their findings represent a significant step towards the application of remote sensing techniques to the estimation of material deposited by mass wasting processes. Similar relationships could not be established for rock fall and debris flow sites.

Deoja *et al.* (1991) present a through examination of techniques and factors used in the analysis of individual slopes for the purpose of risk assessment related to the construction of mountain roads throughout Hindu-Kush Himalaya. Through dozens of examples, case studies and detailed investigations, the authors present comprehensive guidelines and approaches to the mitigation of slope instability and bank erosion with the main goal of reducing the risk posed by these hazard processes to mountain roads. One of their main conclusions is that the alignment of roads closer to ridges and well up slope of river channels significantly reduces the risk of road damage or destruction.

The active site at Luggar Bhati was first examined by Tolia *et al.* (1997), following a major landslide that occurred there in 1995 which killed 22 people, injured several more and caused damage to the transportation network between Kullu and Manali. Detailed analysis of the site and climatic conditions leading up to and, after the failure, reveal that the landslide was caused by abnormally high water levels on the Beas River following several days of intense and prolonged precipitation. The saturated slope was subjected to severe bank erosion several days before the failure, however, the authors also point out that the slope was pre-disposed to previous, smaller slump failures due to the construction of a secondary highway at the base of the slope several years prior. Considering the isolated nature of this event, the relatively high death toll is attributed to the presence of a highway maintenance crew present at the time of the disaster. The heavy rains and consequent flooding that caused this event also triggered many other smaller failures along many sections of the Beas River in 1995. In response to this failure, the authors suggest that the left bank road be realigned to a position higher up the slope, above the Beas floodplain, echoing the recommendations put forth by Haigh *et al.* (1993).

Research carried out on individual slopes leads to a better understanding of the forces that govern slope stability at the micro-scale. Such studies are often commissioned for the purpose of designing or redesigning specific mitigation structures and to implement control measures that would decrease the risk posed by the slope to the affected human elements. As has already mentioned, this scale of analysis is impractical and prohibitively expensive to carryout for larger areas (i.e. watersheds or valleys), yet the information gleaned can be scaled down and implemented in smaller scale studies and so represents a very valuable contribution to our understanding of slope stability and the factors controlling mass movement activity.

1.2.2 Factors

Knowledge of the operation of preparatory and triggering factors is essential for the accurate estimation of risk due to hazards in an area. Most preparatory factors including lithology, rock structure and tectonics are universal in that they exert strong controls over where slope stability or inundation sites are likely to be found regardless of the geographic area being considered. Triggering factors associated with weather and climate (i.e. temperature and precipitation), earthquakes, landforms and human activity are also ubiquitous because they are widely recognized as the dominant forces that actually initiate slope failures, debris flows, floods and rock fall activity. The specific combination of preparatory and triggering factors, however, differs for each physically and culturally distinct geographic region so that the mechanisms driving slope instability and flooding in one area cannot be automatically applied to other regions where climate, geology, slope, and even land use/cover history are different. An examination of previous research on preparatory and triggering factors is presented below with the aim of identifying those that are used most commonly in similar environments to the Himalaya and the Kullu Valley.

1.2.2.1 Tectonics

Several authors have undertaken Himalaya-wide investigations of tectonic and neotectonic activity in order to assess the potential for earthquake activity based on historical records, observations and measurements (Vita-Finzi, 2002; Valdiya, 1999). Chaudhury (1995) provides a thorough review of earthquake activity for the entire Himalayan range by examining the history of seismic activity as well as a number of key individual events that have occurred here since record keeping began in 1869. The entire Himalaya is classified as zone IV or V, where earthquakes intensities of VIII and IX and above on the Modified Mercalli Intensity Scale, are known to occur. Within a 250 km circular radius of Dehra Dun (which includes the Kullu Valley), the recurrence period of potentially devastating Magnitude 7.0 earthquakes is a relatively short 3.6 years. Scheidegger's (1998) research in western China at the eastern edge of the Himalaya confirms the influence of tectonic predesign on slope stability by demonstrating that "Landslides are the result of sudden changes in long-term response caused by minute changes in the initial conditions" (Scheidegger, 1998, p. 45). "Initial conditions" refers to the tectonic stress fields present within the rock mass due to the history of orogenic activity. "Sudden changes" are the triggering mechanisms such as earthquakes, oversteepening of the slope, or increased pore-water pressures. On the basis of a thorough review of earthquake activity in the Himalaya over the past two millennia, Bilham (2004) demonstrates that the area of northwestern India may be overdue for a large ($M < 8.0$) earthquake. Specific attention was paid to the development of seismic gaps along two thirds of the Himalaya over the past five centuries, the rate of plate convergence and the fact that most of the tectonic deformation results in plate fragmentation rather than actual plate deformation which renders the area prone to frequent seismic activity.

The Himalaya represent one of the few tectonic zones on earth where a continental crust underthrusts another continental crust resulting in a thicker crust and a mountain range in the interior of a continent which, is susceptible to large magnitude, shallow earthquakes (Zhao *et al.*, 1993 *in* Kayal, 2001). Peak ground accelerations of 3.2 m s^{-2} have been recorded and ample evidence of neotectonic activity such as diversion of streams by landslides, uplifted river terraces, entrenched rivers and the presence of zones of active mass movement all point to the fact that earthquakes play a major role in reshaping the landscape through various denudational processes (Panikkar and Subramanyan 1996). Rates of uplift ranging from 1.5 – 5 mm y^{-1} and denudation (0.7 – 5 mm y^{-1}) are amongst the highest recorded anywhere in the world (Froehlich and Starkel, 1993) with much of the micro-earthquake activity in Himachal Pradesh occurring above the plane of detachment in the zone of the Main Boundary Thrust (MBT) at depths of 0 – 20 km (Kayal, 2001).

Earthquakes are widely recognized as triggers of mass wasting processes (Barnard, *et al.*, 2001; Tianchi, 1994; Cruden, 1985) and, in some areas, they have been recognized as the primary triggering factor (Espizua and Bengochea, 2002; Pascual, 2001; Alford *et al.*, 2000; Bloom, 1990; Smadja, 1992; Whalley, 1984). Other authors have focused more on recent tectonic activity claiming that increased earthquake activity in certain regions is accelerating the pace of erosion and mass movements (Paul *et al.,* 2000). Rodriguez *et al.* (1999) and Keefer (1984) have determined that magnitude 6.6 earthquakes are capable of triggering landslides within an area of 5,000 km^2 and within 100 km of the epicenter. Specific measures used to quantify the relationship between faults and lineaments and denudation processes include density (Dhakal *et al.*, 1999; Atkinson and Massari, 1998; Rowbotham and Dudycha, 1998), distance (Chung and Fabbri, 1999; Sarkar *et al.*, 1995) and position above or below the Main Central Thrust (MCT) (Marston *et al.* 1998). Earthquakes are most often associated with landslide and rock fall activity and less so with debris flow or flooding events because the latter two processes are more closely controlled by hydro-climatic rather than seismic factors.

1.2.2.2 Bedrock and Surficial Geology

Factors relating to bedrock and surficial geology can be categorized into lithology, bedding geometry and structure, faults and lineaments, soil/material properties, and tension cracks and jointing. Geology is generally accepted as the main preparatory factor affecting almost any mass movement phenomena (Espizua and Bengochea, 2002; Mason and Rosenbaum, 2002; Garland and Oliver, 1993; Cruden, 1985; Whalley, 1984). Dhakal *et al.* (1999), Atkinson and Massari (1998) and Irigaray *et al.* (1994) refer to geology as the most important factor affecting landslide activity. Some authors consider lithology and structure separately, depending on the resources available and the objectives of their study. Donati and Turrini (2002) and Panikkar and Subramanyan

(1996) consider lithology as the most important factor affecting mass movements while Suneja (1977) identifies it as the dominant factor affecting slopes in the Kullu Valley, stating that instability is closely associated with zones of differential weathering where weaker weathered rocks are in contact with more resistant rocks. Espizua and Bengochea (2002) have found that landslides occur more frequently in massive rocks which detach along bedding planes or joints, whereas debris flows are initiated in weaker, friable rocks. Mass movements in the Himalaya have been recorded in clays (Suneja, 1977), highly jointed and shattered quartzites and colluvium (Paul *et al.*, 2000), epidiorites and phyllites (Sarkar *et al.*, 1995) and Higher Himalayan crystallines (Saha *et al.,* 2002). Measurements of strike and dip (Atkinson and Massari, 1998; Atkinson *et al.*, 1998), joint density and size (Mason and Rosenbaum, 2002) and the presence of tension cracks (Whalley, 1984) are considered important inputs into slope stability analysis at various research scales. Suneja (1977) also found that openings such as potholes, burrows and tubes created by chemical weathering or biotic processes influence soil structure and thus stability in the Kullu Valley.

Characteristics of unconsolidated materials considered in many studies of natural hazards include type of material, thickness, and specific properties such as grain size, particle cohesion, weight per unit volume, and internal friction angle. The level of detail with which unconsolidated materials are described greatly depends on the scale of the study. At small and regional scales, only material type and perhaps thickness can be determined with any accuracy, whereas the remaining parameters mentioned above are often included in studies focusing on individual slopes. Slope failures in the Himalaya occur in a variety of surficial materials types including clays (Mason and Rosenbaum, 2002; Blaschke *et al.,* 2000; Jäger and Wieczorek, 1994), glacial deposits (Singh and Pandey, 1996) and colluvium (Baeza and Corominas, 2001; Paul *et al.,* 2000). Material thickness has been identified as second (Zisheng and Luohui, 2004) and third most important (Baeza and Corominas, 2001) in terms of locating landslides while Blaschke *et al.* (2000) found shallow layers of unconsolidated material to be more susceptible to mass movements. Specific factors that influence slope failure including soil cohesion (Mason and Rosenbaum, 2002), internal friction angle (Cruden, 1985) and various measures of soil weight and saturation (Mason and Rosenbaum, 2002; Iida, 1999; Garland and Oliver, 1993) are often included in large-scale engineering studies and can serve as input into factor of stability calculations for particular remediation projects.

1.2.2.3 Geomorphology

Landscapes and their evolutionary history can be described using geomorphological parameters including slope gradient, aspect and shape, relief, drainage density, and measures of factors relating to specific denudational processes. The specific geomorphic factors used to assess landslides, debris flows, floods and rock falls are discussed below. The relevance of most factors to the determination of slope stability undoubtedly varies from region to region, yet many researchers agree that slope gradient is perhaps the most important factor predisposing slopes to a range of mass wasting processes (e.g. Rowbotham and Dudycha, 1998; Ellen and Mark, 1993).

Slope gradients associated with known sites of instability vary depending on material thickness, climate, hydrology, lithology, structure and geomorphic history from low values between 9° - 12° in clays studied by Jäger and Wieczorek (1994) to more common values between 25° to 40° (Dhakal *et al.*, 1999; Sarkar *et al.*, 1995; Irigaray *et al.*, 1994). Baeza and Corominas (2001) and Blaschke *et al.* (2000) simply state that higher slope gradients are more important in terms of slope instability than lower gradients and Iida (1999) found that the incidence of landslides increases sharply above 35°, while Zisheng and Luohui (2004) warn that cultivated lands should not be developed on slopes greater than 16° in areas where material cover is thin. Slope aspect is considered equal or secondary to slope gradient by Donati and Turrini (2002), Mason and Rosenbaum (2002), Zhou *et al.* (2002), Atkinson and Massari (1998) and others. Aspect has a strong influence on factors related to climate and weather, allowing colder slopes to accumulate more snow which lasts longer leading to more intense chemical and physical weathering due to freeze-thaw activity according to Espizua and Bengochea (2002). Marston *et al.* (1998) found that windward slopes are subject to monsoon storms and receive most direct solar insolation, subjecting soils to numerous wet-dry cycles, which also promotes the chemical and physical breakdown of rock material, an important precursor to mass movement. Relative elevation or relief can also influence the degree to which slopes affect local circulation patterns in addition to directly affecting gravitational potential or the energy available for the transport of material downslope (McDougall and Hungr, 2004; Abele, 1994; Evans and Clague, 1988). Some authors consider relief as the second most important factor (Dhakal *et al.*, 1999) or a very important factor (Zhou *et al.*, 2002). Relief is governed by lithology, structure and depositional and erosional conditions specific to each region (Vuichard, 1986). Baeza and Corominas (2001) associate higher elevations and relief with higher precipitation amounts which relates this factor to important triggering mechanisms controlled by weather and climate.

Another parameter related to slope is its local "shape" (Iida, 1999; Atkinson *et al.*, 1998). The shape of a slope can be measured either in cross-section (Baeza and Corominas, 2001) or along the profile and is usually described in terms of concavity or convexity. In their study area, Atkinson and Massar (1998) found that most landslides were associated with concave slopes and shape was the second most important factor governing the location of landslides. Baeza and Corominas (2001) use an additional qualifier termed "complexity" which describes how frequently slope aspect and gradient change over a unit distance, concluding that highly complex slopes are more often associated with slope failures. More regional-scale investigations of slope shape lead to the identification of larger slope units called landforms. Specific landforms linked to slope instability include dipslopes (Rowbotham and Dudycha, 1998), colluvium-filled hollows (Baeza and Corominas, 2001) and valley walls oversteepened by glaciers following their retreat (Abele, 1994; Evans and Clague, 1988). Atkinson and Massari (1998) and Atkinson *et al.* (1998) also use a measure of landform roughness to determine areas prone to landsliding. Chung and Fabbri (1999) report on the use of geomorphological units which serve as input into a hazards analysis and are based on an amalgamation of various geomorphometric parameters including altitude, topography, aspect and slope combined to create areas with homogeneous morphology. Some authors extend Chung and Fabbri's hazards analysis to include parameters used to quantify the geomorphology of watersheds or drainage basins. Some of these parameters include mean slope gradient (Baeza and Corominas, 2001), basin area (Atkinson and Massari,

1998) and length (Baeza and Corominas, 2001), drainage density (Dhakal *et al.*, 1999; Rowbotham and Dudycha, 1998; Bloom, 1990), and distance from valley head (Chung and Fabbri, 1999). Panikkar and Subramanyan (1996) found that 85% of all landslides in their study area were located within 200 m of stream channels, indicating a close relationship between fluvial erosion and groundwater conditions, and slope instability.

Flood hazard is often assessed on the basis of the statistical analyses of hydrological data, often in conjunction with physical channel measurements and investigations of erosional and depositional features that are indicative of peak stage which could be converted to flood discharge estimates (Wohl, 1995). The establishment of flood discharge volumes and their approximate frequencies is an important component to regional hazard assessment because slope failures in the Himalaya are often due to the undercutting of slopes by fluvial erosion (Barnard *et al.,* 2001). Sah and Mazari (1998) report that a variety of slope failures were triggered along the outside of meander loops along with significant erosion caused by turbulence of the overflowing Beas River thus the influence of fluvial activity on mass movements should not be undersestimated.

Large-scale investigations of debris flow hazard and rock slope stability require more detailed input data than discussed above for the purpose of risk analyses at individual sites. Aulitzky (1994) and Caine (1980) identified the following factors which are used to estimate debris flow hazards in the Himalaya; maximum particle size/volume, maximum thickness of single debris layer on the cone, gradient of debris cone, character of discharge on debris cone and location of potential debris volume in source area. Ellen and Mark (1993) predicted the distribution of potential sites, volume of potential failures and frequency of initiation using estimates of weathering intensity, evidence of historical failures from visible scars and by combining weathering rate, combination of average volume and slope gradient, and local historical probabilities of failures, respectively, in order to model debris flow hazards in their study area. Focusing on rock slopes, Abele (1994) concluded that large scale rockslides will occur only after a long period of rock disintegration followed by a long-term persistence of a stable abutment supporting the lower slope. These conditions allow for the accumulation of a sufficiently large volume of rock debris to generate a large magnitude rockslide. Barnard *et al.* (2001) found that most rock fall activity occurred at higher elevations (i.e. above 1,500 m) but that volumetrically, they were insignificant in terms of their contribution to the overall rate of denudation in their study area. Particular factors often considered in large-scale rock fall, avalanche and slide studies include bulk weight of material (Crosta *et al.,* 2003), angle of shearing resistance (Whalley, 1984), unit pressure (Whalley, 1984), hydrostatic pressure within rock face (Whalley, 1984), elastic modulus (Crosta *et al.*, 2001), friction angle (Crosta *et al.*, 2001), rock cohesion (Crosta *et al.*, 2001; Whalley, 1984) and dilitancy (Crosta *et al.*, 2001). Several examples of research related to the factors used to assess slope stability and hazard potential in the Himalaya and elsewhere are provided below.

According to Shroder Jr. (1998), maximum denudation in the western Himalaya is highly correlated with zones of high seismicity and controlled by bedrock geology and climate. He identified slope failure as the main process reshaping the present-day Himalayan landscape and calls for more research on denudation rates and "...distributions, and volumes of sediment involved in shallow erosion" (Shroder Jr., 1998, p. 102). This is echoed by Carson (1985) who concluded that "...mass wasting is the dominant process in the evolution of natural slopes throughout much of the Nepalese

Himalaya (Carson, 1985 *in* Vuichard, 1986, p. 48). Through detailed investigations of slopes in northern and western Himalaya, Yudhbir (1997), explored the interaction between geology, geomorphology, ground water, engineering works (e.g. road or canal construction) and slope instability and concluded that a minimum acceptable degree of slope stability could only be attained once a "…proper understanding of the working of a site…" has been achieved through careful map interpretation and diligent field surveys (Yudhbir 1997, p. 47). Abele (1994) attributes the occurrence of large rockslides to the long-term disintegration of rock comprising the slope and the presence of a supporting abutment on the lower slopes of the rock face which allows only small rock fall failures to occur until a critical stage is reached when the entire rock slope fails *en masse*. Actual triggering events of large rockslides may involve dramatic changes in topographic, hydrological or glacial conditions.

Through several case histories ranging from glacial deposits in New York State, USA, to the Siwalik Hills of Northern India, Yudhbir (1997) explains the geomorphic changes that have occurred at each site, leading to slope failure and the loss of property and lives. Processes including valley widening by fluvial erosion, internal erosion of slope sediments, human-induced excavation of slopes, lack of careful planning, and the presence of ancient landslide deposits have all been associated with landslide disasters. Yudhbir's (1997) study demonstrates the strong effects of geomorphological history on the susceptibility of an area to landsliding. Geomorphological history can also be described in terms of weathering processes which, as stated by Bloom (1990), are a necessary precursor to the mass wasting of rock material down slope predominantly under the influence of gravity. The break down of rock material must precede slope failure by mass wasting processes such as soil or rock creep, debris or earth flow, debris slide and rock avalanches, and rock fall. The length of time a slope or portion thereof is exposed to weathering process will affect its potential for failure at some time in the future. However, as pointed out by Flageollet (1996), the element of time is often disregarded or considered too difficult to establish accurately in many studies of mass movements. Flageollet (1996) attempts to standardize the concept of activity as it pertains to the return period of various mass wasting processes through a review of available literature and suggests that it should be an inherent component in hazards mapping.

The inherent complexity and intricacy of the Himalayan landscape makes it nearly impossible to apply the results derived from one area to another. Before such attempts can be made it must be established that such physical factors as relief, geology and land use/cover and anthropogenic influences including accessibility, pattern of historical land use/cover change, general socioeconomic conditions and control and management of forests are nearly identical or there are strong justifications for proceeding if they are not (Barnard *et al.*, 2001; Schickhoff, 1995).

1.2.2.4 Weather and Climate

Weather and climate, expressed in terms of the quantifiable parameters temperature and precipitation, directly affect slope stability and flooding processess. Changes in temperature and precipitaiton not only influence the rates of physical and chemical weathering processes while directly affecting vegetation cover which, as will be discussed in Sections 2.1.5. 3.6 and 3.7, has direct consequences on slope stability, they also serve as the main triggering mechanisms for landslides, rock fall and debris flow processes (Barnard *et al.*, 2001; Tianchi, 1994; Ellen and Mark, 1993; Bloom, 1990 and others). In most hazards-related studies, the effects of weather and climate on slope stability are established by measuring precipitation amount, intensity and duration, antecedent moisture content, pore-water pressure within rocks or surficial material, ground water levels, rates of rapid melt events, and temperatures at a given interval. Numerous researchers have attempted to derive a threshold precipitation rate or intensity above or below which mass movements are very likely or very unlikely, respectively, to occur for a particular area with varying degrees of success (Baeza and Corominas, 2001; Freohlich and Starkel, 1993; Garland and Oliver, 1993). The research carried out by Caine (1980) is an exception in that the author derived a globally-applicable equation for either rainstorm intensity or duration beyond which shallow landslides or debris flows are likely to occur based on a thorough analysis of hazards studies from many parts of the world. Other general thresholds are offered by Barry (1992) who found that widespread slope failures often occurred following extreme precipitation events which is defined as representing 10% – 20% of the total annual rainfall in one event, and Garland and Oliver (1993) who report that continuous rain events lasting 3-days or longer and days with the maximum monthly wet season value were closely related to landslide activity (Aulitzky, 1994). Prolonged and/or intense rainfall or rapid melt events raise ground water levels leading to increased pore-water pressures within rocks (Whalley, 1984) and surfical materials (Chen and Lee, 2003; Bloom, 1990; Cruden, 1985). Garland and Oliver (1993) found that more landslides tend to occur towards the end of the rainy season when antecedent moisture conditions are high (Mason and Rosenbaum, 2002) and ground water levels are already elevated, allowing threshold conditions to be attained by less extreme precipitation or melt events.

Although precipitation is regarded by many authors (e.g. Zhou *et al.*, 2002; Barnard *et al.*, 2001; Caine, 1980) as the most important trigger of mass movements, Pascual (2001) acknowledges that there is a high level of uncertainty associated with predicting landslides as related to rain events in general and intensities and duration in particular. Sah and Mazari (1998) claim that the recession of the colder climatic belt to higher altitudes in the past several decades has subjected the slopes in the Kullu Valley to a more moist regime. However, Singh and Roy (2002) draw attention to the fact that the existence of wide-ranging micro-climatic regimes and the absence of long-term climatic records make it difficult to assess the effects of climatic variability on the mountain ecosystem. In order to address the issue of predictability of rainstorm events capable of triggering mass wasting processes, Barros (2004) and Barros *et al.* (2004) have carried out a Himalaya-wide analysis of cloud, rainfall, large circulation patterns and topography using remote sensing techniques in order to improve the accuracy of predicting the spatial and temporal organization of precipitation in the Himlaya. Barros *et al.* (2004) found a strong presence of convective weather systems during the monsoon, particularly during afternoon and at night, and conclude that the timing of heavy rain events is linked to the presence of meso-scale convective complexes and Bay of Bengal monsoon depressions that venture into the lesser Himalayan region. Further work by Barros (2004) established a link using global circulation models (GCMs) between large-scale atmospheric dynamics and rare events producing significant amounts of precipitation over one to three day periods which corresponds to the intensity/rate precipitation thresholds derived by Aulitzky (1994), Froehlich and Starkel (1993) and Garland and Oliver (1993). Results from selected previous research efforts are discussed in detail below.

Focusing on the geomorphic responses of mountain slopes along a Central Asian transect to climatic and environmental changes during the Holocene, Starkel (1998) found that aspect of mountain ranges is a significant factor in determining the amount of rain received on a slope and its geomorphic activity. Starkel (1998) observed that south-facing slopes of mountain ranges, which generally receive twice as much rain as north-facing slopes, were very prone to shallow landslides and mudflows, particularly in deforested sections (Starkel, 1972b; Brunsden *et al.*, 1981; Froehlich and Starkel, 1987 *in* Starkel, 1998).

Rainfall intensity conditions that are known to have caused shallow translational landsliding and debris flow activity were examined by Caine (1980). This author carefully compiled and analyzed a record of previous failures investigated by other researchers from various parts of the world. In doing so, he mathematically defined two rainfall intensity/duration thresholds (I) between which most of the slope failures recorded in past literature have taken place (i.e. $I = 14.82\ D^{-0.39}$ and $I = 388\ D^{-0.514}$) where D is the duration of a rain event in hours. The potential applications of these thresholds are to define an extrinsic minimum rainfall that is separate from factors related to slope materials, and to quantitatively evaluate the degree of hazard associated with shallow landslides by translating the intensity/duration threshold into an approximate recurrence interval by comparing it to standard duration/frequency curves for the particular area of interest. Since these thresholds represent the least stable scenarios, actual soil and slope conditions may render the slopes more stable, allowing for a margin of safety. Garland and Olivier (1993) noted that landslide activity in humid, sub-tropical regions tends to increase towards the end of the wet season when regolith moisture is high and the potential for subsequent rainfall events to raise pore-water pressures above critical levels is heightened. Garland and Olivier's (1993) conclusions demonstrate the importance of antecedent moisture conditions on slope stability, suggesting that prolonged rainfall over several weeks or months may be as important as the occurrence of short, extremely intense events when it comes to shallow landsliding.

Chen and Lee (2002) used data from 56 landslides that were triggered in natural terrain on Lantau Island, Hong Kong, by an extremely intense rain storm on 4-5 November, 1993. In this area, landslide activity increases substantially with the occurrence of high-magnitude rainfall events of short duration, with an estimated threshold intensity of 70 mm h^{-1}. During such events, a transient water table develops at the interface between the highly permeable colluvium and the less permeable underlying rocks. This causes seepage and pore-water pressures to rise, reducing granular cohesion and increasing weight of the regolith. Under these conditions, the driving forces within the slope are elevated above resisting forces and the material begins to mass waste downslope under the influence of gravity.

1.2.2.5 Land Use/Cover Change

The discussion above demonstrates that landslide activity tends to be closely associated with such physical factors as lithology and structure, slope gradient and aspect, proximity to fault lines, and drainage courses. Although several of these factors serve both a preparatory and triggering role (e.g. land use/cover, tectonic activity, fluvial erosion and elements of climate), only land use/cover change also directly affects what specific elements of the cultural and natural landscape are at risk. Land use/cover change can alter risk, defined as the product of the temporal and spatial distribution of natural hazards and the susceptibility of specific elements of the human landscape to these hazards, in two distinct ways; firstly by materially changing the location, magnitude and/or frequency of natural hazard processes and; secondly by changing the exposure of anthropogenic elements to natural hazards. In one of the few studies addressing the contribution of settlement expansion into active zones of slope instability, Aulitzky (1994) found that "...the reasons for destruction during the four extraordinary disasters of 1965 and 1966 in Tyrol..." were the construction of housing in "dangerous areas" and "inadequate flood control" which combined, accounted for over 77% of the damage related to human influence and 52% of the damage overall (Aulitzky 1994, p. 307).

The bulk of hazards research in the Himalaya has focused on the manner in and degree to which changes in land use/cover alter the location, magnitude and/or frequency (collectively, *activity*) of mass wasting processes. The role of land use/cover change in altering the other, perhaps more important element of risk, namely the exposure of people and infrastructure, is almost completely ignored. Furthermore, future changes in the risk of an area are examined almost solely on the basis of how probable changes in land use/cover will affect the activity of natural hazard processes without fully appreciating the possibility that a change in vulnerability due to the expansion or intensification of infrastructure may have a more direct impact on total risk. Perhaps an obvious explanation for this apparent oversight is that the aim of much of the previous research has been to answer the main question posed by the Theory: What are the effects of land use/cover change in the mountains on the floodplain areas to the south of the Himalaya? (Zurick and Karan, 1999). In this context, there is apparently no need to evaluate the risks in the upper watersheds which are the source of the supposed increases in sedimentation and erosion because the elements at risk are far downstream, on the alluvial plains and deltas of the Ganges and Brahmaputra Rivers. Evidently, the inhabitants of the upper watersheds in the Himalaya are the foci of attention not because their landscape is being dramatically altered by the expansion and intensification of large-scale development projects including roads, tourism-related infrastructure, dams and reservoirs, and commercial logging, but because they are irresponsible stewards of the very land that has sustained them for centuries if not millennia.

The current and future spatial patterns of risk at the local level resulting from the present and planned distribution of infrastructure, respectively, needs to be assessed in each and every Himalayan valley undergoing rapid and unchecked land use/cover change. It is necessary to determine to what degree land use/cover change is materially altering the activity of natural hazard processes and to assess the impacts of the expansion and intensification of infrastructure into unstable areas in order to determine total risk. This type of research is of paramount importance given the growing body of evidence which supports the theory that the rapid removal of vegetation followed by poor stewardship and management of the devegetated area has negative and direct consequences on slope stability in many areas of the Himalaya as well as other mountain regions (e.g. Riebsame *et al.*, 1996).

Vegetation cover was identified as an important factor influencing landslide activity by Mason and Rosenbaum (2002), Zhou *et al.* (2002), Dhakal *et al.* (1999), Atkinson and Massari (1998), Aulitzky (1994), Irigaray *et al.* (1994), and others in various mountain regions in the world. The frequency of landslides and other shallow slope failures was found to be highest in areas under cultivation (Temesgen *et al.*, 2001; Rowbotham and Dudycha, 1998; Froehlich and Starkel, 1993), especially in degraded, abandoned or marginal agricultural terraces (Pascual, 2001; Rawat and Rawat, 1994) as well as areas classified as "barren" or devoid of vegetation (Saha *et al.*, 2002; Temesgen *et al.*, 2001; Sarkar *et al.*, 1995; Rawat and Rawat, 1994,). Pascual (2001) and Marston *et al.* (1998) blame the increase in slope failure activity specifically on poor planning and improper management of drainage and runoff from agricultural fields in their respective study areas. Land use/cover change brought about by human activities over relatively short periods of time (within several years) are also known to lead to more frequent landslides, debris flows and floods. The conversion of mature forests to agriculture, horticulture, grazing land, clearcuts, cultivated terraces and orchards have all been associated with an increase in the activity of erosion and denudation processes (García-Ruiz and Valero-Garcés, 1998). Marston *et al.* (1998) reports that mass movements are 17 times more likely to occur in clearcuts than in forested areas, which is in close agreement to research carried out by Froehlich and Starkel (1993) who found that following heavy rains, the frequency of mass movements was 10 to 20 times higher in cultivated areas compared with forest stands. Marston *et al.* (1998) also report that while shallow failures were closely associated with unvegetated slopes, larger landslides of higher magnitude and lower frequency occurred independent of vegetation cover which may explain observations by Irigaray *et al.* (1994) that most landslides were found in areas under forest cover.

The clearing of forests for agriculture, construction, resource extraction and other economic activities results in the removal and/or slow degradation of tree roots which contribute significantly to the shear strength of the upper-most meter of soil (Cruden, 1985) and negatively impacts the runoff regime on the affected slopes (Oyarzún, 1995). Undisturbed areas and dense forest stands reportedly have the lowest runoff rates and conversely highest rates of infiltration (Baeza and Corominas, 2001; Oyarzún, 1995). However, research carried out by Rawat and Rawat (1994) shows that runoff rates from forest areas can exceed rates from anthropogenically disturbed areas by a factor of 3 during April, the driest and hottest month in the Nana Kosi watershed in the central Himalaya. Moisture that has infiltrated into the ground can rapidly raise water table levels, leading to heightened pore-water pressures within the soil resulting in a reduction in shear strength and increase in shear stress due to weight of the material (Chen and Lee, 2003; Garland and Oliver, 1993).

Other human-induced land use/cover changes known to actually trigger mass movements include road construction (Chung and Fabbri, 1999), specifically the removal of supporting toe material from the base of a slope (Barnard *et al.*, 2001), expansion of infrastructure and related construction activities (Sah and Mazari, 1998), and loading of the upper portions of steep slopes (Tianchi, 1994). The acceleration of soil erosion and increase in frequency of erosion and denudation processes in mountain areas due to land use/cover changes brought about by human activity (Barnard *et al.*, 2001; Marston *et al.*, 1998; Sah and Mazari, 1998; Singh and Pandey, 1996) should significantly raise the level of awareness of the impacts people are having on the activity of natural geomorphic processes and the risk these processes pose to people and related infrastructure. Land use/cover change has the potential to rapidly alter both the physical parameters affecting the predisposition of a slope to instability and the triggering mechanism which determine when a slope might fail. It is thus important to establish or maintain an active land use/cover change monitoring program in areas that are undergoing or may soon undergo rapid human-induced changes to the natural or anthropogenically altered environment in order to accurately predict the effects of these changes on the state of natural hazards in the region.

1.2.3 Themes of Hazard Assessment

The factors reviewed above are often grouped into identifiable themes which are then applied to the analysis of specific hazards. The aim of this section is to highlight some of the common themes used in hazards research by reviewing specific efforts that demonstrate each of the four approaches considered here, that is; geomorphic, mapping, and human impact.

1.2.3.1 Morphologic Studies

Geomorphic approaches to natural hazards research focus on the identification and quantification of landscape change that may have occurred over a certain period of time in order to assess the impacts of those changes on the state of natural hazards in an area.

Gardner (2002) provides an example of an historical approach to the analysis of mass wasting and denudation activity in the Kullu Valley by assessing the impacts of deforestation over a 150 year period combined with a review of available records and interviews with local inhabitants. He concludes that apart from slopes adjacent to roads, there has been little discernable change in the frequency or magnitude of hazardous processes in the study area. Gardner *et al.* (1992), based on field work, map and air photo interpretation and a review of historical documents, proposed a four-step schema for the identification and monitoring of geomorphic and hydrological hazards in high mountain areas. Drawing on experience gained in the Kaghan Valley, Punjab Himalaya, Pakistan and Yoho National Park, Canada, the authors begin with an initial hazard identification that is followed by hazard monitoring, then risk estimation and finally hazard representation. Keenly aware of the general lack or inaccessibility of data in remote mountain areas, Gardner *et al.* (1992) provide a detailed description of the photograph, map and field criteria that can be used to identify multi-process hazards in the field and provide examples of less commonly used information sources, including local long-term inhabitants and oral histories all of which can be useful in defining risk levels and selecting mitigative measures.

Based on research carried out by García-Ruiz and Valero-Garcés (1998), the combination of topographic and climatic heterogeneity superimposed on an altitudinal gradient results in great diversity of geomorphic processes which are further modified by human activity leading to the current state of mass wasting and soil erosion activity on a regional scale. Taking into consideration the entire Himalayan region, Heimsath (2000) recognizes the youthful nature of these mountains and puts both the natural and anthropogenic causes of erosion into perspective by drawing attention to the fact that areas experiencing the highest rates of uplift and denudation are also the least populated, and concludes that human impacts are having a rather negligible effect on overall erosion rates.

On a larger scale, most studies focusing on the analysis of controlling factors begin with the compilation of a hazards inventory which is used to extract the factors for subsequent analysis. Although interpretation of air photos is one of the most common techniques used to derive a hazard inventory, the results of a study by Brardinoni *et al.* (2002) suggest that land use/cover, relation of hazard site to gullies, slope gradient, valley width, slope position and stream connection are all factors which can affect the accuracy of an inventory collected from air photos compared with one collected using fieldwork. Once a reliable inventory has been established, various techniques can be applied to the analysis of factors affecting erosion and denudation process. Marston *et al.* (1998) employed a simple Chi-squared statistic to compare several factors known to influence slope stability in order to determine which was most influential. Pascual (2001) and Suneja (1977) identified geology and the effects of human activity as the main factors associated with landslide activity, while Donati and Turrini (2002) and Zhou *et al.* (2002) agree that landslides are controlled by slope gradient and aspect, land use/cover and proximity and density of drainage channels in their respective study areas. Marston *et al.* (1996) demonstrated that morphometric variables including basin area, perimeter, elongation, relief, and relief ratio, and not forest cover, exert the dominant control on peak flows at 22 ungauged streams located along a 240km long transect in central Nepal. Hearn and Jones (1987) evaluated the value of geomorphological surveys conducted in the period 1974 – 1981 prior to the construction of the 52 km-long Dharan – Dhankuta road in eastern Nepal by assessing the damage caused by a severe storm in September, 1984. Although the road in this area was cut in several locations, with culverts blocked and many mitigative structures failing, the authors concluded that most of the road surface, including all of the complex hair-pin stacks, remained unscathed due in large part to planning stemming from preliminary geomorphological surveys. The main shortfall of those surveys was the general lack of attention paid to fluvial and debris flow hazards which caused much of the damage following the storm. However, in view of the inherently unstable terrain and temporal and financial constraints associated with road construction in this and many other parts of the Himalaya, Hearn and Jones (1987) concluded that preliminary geomorphological surveys are essential in order to engineer construction that minimizes damage to structures and loss of life and property.

The assignment of weights to factors and the analysis of their subsequent interactions are now most often carried within a geographical information system (GIS) (e.g. Zhou *et al.*, 2002). GIS-based factor analysis often results in the generation of hazard maps showing the relative distribution of hazard classes. Van Westen *et al.* (2003) found that the accuracy of such hazard maps can be significantly improved by incorporating geomorphological knowledge provided by an expert in the field. Their results show a 24% improvement (from 52% to 76%) in the accuracy of a landslide susceptibility map generated using GIS-based indirect bivariate statistical analysis.

More comprehensive approaches to hazard assessment involve the application of geomorphic models which take into account a wide range of processes and variables in order to predict various characteristics of hazard processes. Atkinson and Massari (1998) used multiple topographically-driven GIS-based models to determine general areas of potential slope instability. A simple slope stability model was used to predict areas prone to shallow landsliding and a Hortonian overland flow model was applied to the identification of areas subject to overland flow and to model relative erosional intensity. With the aim of reconstructing the geomorphological evolution of an area, Pasuto and Soldati (1999) analyzed the landscape using homogenous geomorphological units which were derived by mapping past gravitational processes, paying particular attention to their spatial and temporal relationships. Atkinson *et al.* (1998) introduce the concept of generalized linear modeling (GLM) to geomorphology in order to statistically model the simultaneous relation between a single response variable and a set of explanatory variables for an area in the Italian Alps. Suspected and known landslides were surveyed on air photos and in the field in order to establish a set of key independent geomorphological variables which were then used in the linear model to determine which combination of variables was most significant. Geomorphic variables most frequently associated with landslides in the Italian Alps include geology, slope gradient, vegetation type and slope convexity. A number of authors have also included triggering factors into their geomorphological models. Iida (1999) found that the average recurrence interval of shallow landslides is a function of the stochastic properties of rain events and topography, both of which could be characterized by slope angle and a hydro-geomorphological parameter estimating depth of saturated flow based on the Laplacian of elevation.

General circulation models (GCM's) have even been incorporated into GIS-based models in order to assess the effects of climate change on mass movement activity (Collison *et al.*, 2000) and landslide frequency (Dehn and Buma, 1999) although the latter authors conclude that results are strongly dependent on the particular GCM employed.

1.2.3.2 Analysis and Presentation of Hazards and Risks

The spatial distribution of risk is most commonly represented using some type of hazard map. The application of GIS to the development of hazard maps, monitoring land use/cover change, and its utility in organizing, analyzing, modeling, and presenting pertinent hazards information in an efficient and flexible manner is well documented in the literature. The aim of this section is to provide background information on the types of GIS-based hazard mapping techniques in use today in the Himalaya and elsewhere and to draw attention to the specific shortcomings of the reviewed methods in order to address them where possible. For a complete review of techniques and methods used in the preparation of landslide hazard maps and their application to hazard mitigation and risk management, see the works of Hartlen and Viberg (1988), Hansen (1984), Varnes (1984), Panizza (1978), and Kienholz (1977).

Since the mid 1980's, GIS has been the standard tool with which to organize and analyze pertinent parameters related to landslide activity gathered in the field or interpreted from remotely sensed imagery or even historical documents for the purpose of hazard assessment (Irigaray *et al.*, 1994; van Westen, 1993, 1992a, b; Rengers, 1992; Rengers *et al.*, 1992; Van Asch *et al.*, 1992; Soeters *et al.*, 1991; van Westen and Alzate, 1990). The assessment of susceptibility or risk of mountain slopes almost invariably begins with an inventory of the release areas of landslides or surface rupture zones on slopes which are depicted either as points or areas depending on basemap scale. An inventory map provides basic information on the location, spatial distribution, type, and characteristics of mass wasting process identified through a combination of field survey, review of historical records or databases, air photo interpretation, remotely sensed image analysis, and/or terrain modeling (Soeters and van Westen, 1996; Guzzetti and Cardinali, 1990; Einstein, 1988; Hansen, 1984; Wieczorek, 1984; Cotecchia, 1978; Carrara and Merenda, 1976). Whereas surveys, reviewing reports, databases, terrestrial photographs, and air photo interpretation are standard techniques used by earth scientists to identify and locate mass wasting phenomena, the interpretation of remote sensing imagery and terrain modeling are newer methods, with only a few examples of their application to projects outside of academia (Brozovic *et al.*, 1997; Burbank *et al.*, 1996; Mantovani *et al.*, 1996; Gupta and Joshi, 1990).

Although lacking information on probable magnitudes or recurrence intervals of the processes, an inventory map serves as a basic form of hazards map because it shows areas of recent slope instability and perhaps even more importantly, it identifies areas that were susceptible to mass movement in the past. GIS overlay operations allow values to be extracted from factor maps such as land use/cover, slope, aspect, slope profile, and geology for each site and the quick visualization of their distribution in order to uncover spatial patterns and correlation between independent variables (Seijmonsbergen *et al.*, 1989 *in* van Westen, 1994; Rupke *et al.*, 1988). It is advisable to collect as much detailed information about each release site or surface rupture zone (Atkinson *et al.*, 1998; Irigaray *et al.*, 1994) as possible in order to facilitate future comparisons with subsequent inventory maps compiled by different researchers with different levels of geomorphological experience (Zhou *et al.*, 2002; van Westen *et al.*, 1999).

A relative comparison of hazard inventory maps from different dates for the same area constitutes the basis for mass wasting activity maps. Activity maps may also be derived from medium or large scale repetitive field surveys or from the analysis of multi-temporal air photos or remotely sensed imagery (Soeters and van Westen, 1996). The change in mass wasting activity between the two dates is detected by GIS overlay and expressed in total number or percentage of reactivated, new, or stabilized sites (van Westen, 1994). Parise and Wasowski (1999 *in* Parise, 2001) report that activity maps tend to focus on the effects of the temporal evolution of slope movements on particular elements of interest instead of on the causative conditions and processes, yet there is very little evidence of their application to this type of problem in the current literature. The temporal evolution of landslides is driven by the same factors that control all mass wasting activity over relatively short periods of time (i.e. <100 years), namely the occurrence of triggering events such as precipitation or earthquakes and land use/cover change (Wu and Sidle, 1995; Costa and Baker, 1981). Other factors such as lithology, stratigraphic sequence, structural setting, climate, and topography (i.e. slope, angle, aspect, elevation, etc.) are often considered to be static (Irigaray *et al.*, 1994). This justifies the value of activity maps which when combined with land use/cover change information provide the geomorphologist with a means of evaluating how the predisposition of a slope has changed over time due to land use/cover change. It has been reported that for many areas in the Himalaya, landslide scars and other evidence of slope failure are only evident for 1 to 10 years after their occurrence due to the rapid rates of revegetation which quickly obscures much of the visible evidence or "silent witnesses" (Singh and Singh, 1987; Kienholz, 1977; Schweinfurth, 1968). Thus in order to estimate where landslides may have occurred 20 or 30 years ago, it is necessary to; first, establish the combination of factors that characterize known active landslides; second, use this combination of factors to create a susceptibility map for the whole study area and test the map against the locations of known active sites; third, use the inventory map of known landslides to identify areas that were susceptible to failure in the past; and fourth, predict where landslides are likely to occur in the near future based on an established trend in land use/cover change. There has, however been virtually no research on this topic with exception of the work being done by Chung and Fabbri (1999) who reported their intent to use a multivariate analysis of 7 input factors for post-1960 landslides in order to predict the location of pre-1960 landslides.

The main limitation of both inventory and activity maps is the lack of information about any possible associations between the number or frequency of landslides and the specific natural or anthropogenic parameters; as a result they are incapable of conveying the likelihood or probability of occurrence. Yet according to the literature review presented in Section 1.2.2 above, landslides and other mass wasting phenomena are known to be more closely associated with certain elements of the natural and human landscapes than others (Atkinson *et al.,* 1998; Burrough, 1986; Crozier, 1986; Newman *et al.,* 1978). These associations are taken into consideration in landslide susceptibility maps and expressed as the relative likelihood of occurrence. For example, it is well established that landslides in the Himalaya occur more frequently on moderate to steep slopes, in close proximity to faults, and in degraded or deforested areas than on shallow or vertical slopes, far from lineaments and faults, and in well forested or bare rock areas. Differences in likelihood of occurrence between each factor are expressed as classes of relative susceptibility as observed in the field, or derived by overlaying inventory or activity maps onto the factor maps using GIS (Dai and Lee, 2002; Dikau *et al.*, 1996; Mark and Ellen, 1995; Wang and Unwin, 1992; Wieczorek, 1982; Brabb *et al.*, 1971). According to Dikau *et al.* (1996), GIS is best suited to the creation of "...spatial landslide inventories and related information for the elaboration of hazard and susceptibility maps" (Dikau *et al.*, 1996, p. 230). Van Westen (1994) points out that univariate GIS-based analysis of susceptibility was first explored in the late 1970's (Newman *et al.*, 1978) but has found limited appeal amongst other researchers (with the exception of Choubey and Litoria, 1990; Lopez and Zinck, 1991; Brabb *et al.*, 1989; Brabb, 1984) despite the suitability of GIS to this type of multi-layer problem. The works of Kienholz *et al.* (1988), Radbruck-Hall *et al.* (1979), Carrara *et al.* (1978, 1977), and Huma and Radulescu (1978) contain examples of the application of GIS to multivariate statistical analysis of hazards mapping. The main advantage of bivariate and multivariate statistical landslide analyses over qualitative mapping techniques are the "...higher degree of objectivity and better reproducibility of the hazard zonation, which is important for legal reasons" (van Westen, 1994, p. 153). Typically the input factor maps and the individual map classes therein are assigned weights based on the calculated density or total area of mass wasting sites within each class of each factor map or in some cases Bayesian rules for conditional probability (e.g. Bonham-Carter *et al.*, 1990).

In the case of multivariate analysis, the cumulative importance of a suite of input factors is quantitatively assessed using some type of statistical measure of separation such as discriminant analysis or multiple regression analysis (Carrara, 1992, 1988, 1983; Carrara *et al.*, 1991, 1990, 1978). These techniques are almost exclusively applied to the medium scale of analysis because of the typically large databases that are generated which limits their use for very large areas while large scale analyses demand much more precise input data which is seldom available (van Westen, 1994). Baeza and Corominas (2001) used multivariate statistical techniques and 40 independent variables to determine which combination of factors best described the susceptibility of an area in the Spanish Eastern Pyrenees to landsliding. Through a principal components analysis, t-test, and one-way test, 5 pertinent variables were identified (high slope angles, large, unforested watersheds, concave, transverse slopes, and thick accumulations of colluvium) which allowed the authors to discriminate between stable and unstable slopes to a confidence level of over 88%. Using a fuzzy set approach combined with if-then rules, Ercanoglu and Gokceoglu (2002) produced a landslide susceptibility map for an area in NW Turkey. Their results indicate that slope angle exerts the most control on the location of landslide prone areas whereas degree of weathering exerts the least. Rowbotham and Dudycha (1998) applied logistic regression to terrain units derived from several DEM derivatives in order to develop a slope stability model for the Phewa Tal watershed in Nepal. The statistical model coefficients for each explanatory variable were generated using a random selection of half of the terrain units and the other half of the terrain units was reserved to evaluate how well the statistical models matched the expected output. Although their results indicate a 90% concordance rate with sites identified in the field, the main reason for this appears to be their subjective classification of continuous probabilities into 4 unequal stability classes which, the authors state, are based on

"...experimentation in an effort to obtain a stability map that closely approximated the map of the estimated rankings of stability" (Rowobotham and Dudycha, 1998, p. 166). This introduces a very heavy subjective component into their research and results, something that the authors clearly stated they wanted to avoid. However it serves to demonstrate the challenges associated with creating bias-free hazard maps. Atkinson and Massari (1998) and Atkinson *et al.* (1998) applied a generalized linear model to test the susceptibility of an area in the central Apennines of Italy to landsliding. Through an iterative logistical regression they found that slope angle and geology were the most important independent variables controlling the location of both active and dormant landslides, while vegetation cover and concavity of slope were more significant for active landslides. Atkinson and Massari (1998) stress the importance of analyzing the pre-failure surface conditions (e.g. slope and land use/cover) when determining the causative factors of landslides. Maps showing past landslide susceptibility based on a reclassification of several input factor layers using an inventory of known active sites combined with historical land use/cover maps would allow for the evaluation of pre-failure conditions.

The main assumption in these types of analyses is that the combination of factors associated with known landslides can be used to detect future landslide prone sites in the remainder of the study area. At the very least, this assumption is scale and time dependent even if all of the influential variables have been considered, which itself is unlikely with the dozens of factors and very complex interactions between these factors governing slope stability. Chung and Fabbri (1999) address this assumption by dividing an inventory map of landslide scarps for a catchment of the Rio Chincina in central

Colombia into pre- and post-1960 events, and then using five different probability models to predict the later events based on a statistical, multivariate evaluation of 7 factor maps of the earlier events. Frequency ratios of landslide occurrence were used to assign weights to each of the classes in maps of lithology, geomorphological units, land use, slope, distance to valley head, distance to road, and distance to faults. The authors also attached qualitative weights to each class based on expert knowledge in an attempt to improve landslide predictability. They conclude that multivariate regression is better at predicting landslide-prone slopes than Bayesian probability methods because the inclusion of expert knowledge improves predictability in instances where the database is unable to provide "reasonable" support for a prediction. Dividing the initial inventory map into a "control" group and a "test" group allowed for an immediate assessment of model robustness.

This type of control and test group approach can also be applied to inventory maps of active sites by using half of the known sites to extract characteristics associated with failed slopes to predict the location of the other half of the known sites, swapping the test and control groups to extract another set of characteristics then statistically testing for any differences between the two datasets and resulting susceptibility maps. Several authors have advanced this concept by extracting training information from several input factors such as slope, relief, geology, and land use/cover for known landslide sites and using that information to build a multivariate statistical model which is then extended to the entire study in order to identify other areas with similar conditions (Carrara *et al.*, 1991, 1990; Bernknopf *et al.*, 1988; Carrara, 1988). The training or classification of factor maps is based on either the percent area or the frequency of landslides found in each class of each factor map. Classes with higher instances of active sites are assigned higher ranks in the subsequent reclassification and combination of factor maps to produce a susceptibility map for the whole area. Landslide density can also be expressed in terms of an isopleth map which is created by connecting areas with an equal number of landslides or landslides per unit area with isolines. Isopleth maps allow for a quantitative comparison of the percentage of land that has been affected by previous mass wasting activity in a given area and are a quick way of identifying areas which may require more detailed slope stability analysis (Bulut *et al.*, 2000; DeGraff and Canuti, 1988; DeGraff, 1985; Wright *et al.*, 1974).

The final step in heuristic landslide mapping is to consider the actual "...degree of loss to a given element or set of elements at risk resulting from the occurrence of a natural phenomenon of a given magnitude" (Varnes, 1984 *in* Parise, 2001, p. 699). Beyond the information contained in susceptibility maps, vulnerability maps include data on the magnitude and frequency of occurrence of mass wasting processes at specific sites as well as the timing of probable triggering events. The collection of magnitude and frequency data is an expensive and time consuming process usually requiring extensive field work by several experts at each site to establish the history of events by means of an interpretation of stratigraphic sequences of deposits, a review of historical records and documents, or an examination of lichen growth. Although the actual triggering mechanisms are most often precipitation or seismic in nature, the exact relationship between rainfall or earthquake events of a particular magnitude and mass wasting activity is still poorly understood (Capecchi and Focardi, 1988 *in* van Westen, 1994; Keefer *et al.*, 1987; Crozier, 1986). Further more there is a need to gather "...information regarding distribution, type, and economic value of each element at risk…" (Parise, 2001, p. 699). Obviously the collection and analysis of this type of data goes beyond the abilities of an earth scientist or geomorphologist and into the realm of other disciplines including economics and other social sciences.

Inventory, activity, susceptibility and vulnerability maps mainly depict portions of slopes where mass wasting activity has already occurred or where it may likely occur in the future. A more comprehensive representation of hazards, however, should also include potential deposition areas for each of the processes considered. Run-out modeling can be used to estimate deposition areas of hazardous processes such as landslides or debris flows using parameters such as velocity, flow depth and deposit depth of the failed mass (Hungr, 1997). The methods and techniques used to model landslide and debris flow deposition characteristics are continuously undergoing refinement (Brunsden, 1999). For early development and initial applications of empirical models see the works of Davies (1982), Hsu (1975), Abele (1974), Scheidegger (1973), and Heim (1932). The most basic post-failure parameters that are typically modeled are the 2-D planimetric extent of the deposition areas and their distribution throughout the study area. More advanced models take into account entrainment of material along the flow path, rheological properties of the sliding mass and anisotropic frictions and are capable of predicting velocity, flow depth, and depth of deposits in full 3-D space in real time (Hungr, 1997). The generally high level of approximation of input parameters required by empirical models makes it difficult to fully describe the actual failure mechanism, exact pre- and post-failure volume and duration of process. Most analytical or numerical models function at very large scales (<5 km^2) and are mainly applicable to the simulation of flow behavior, runout prediction and hazard zonation at individual sites.

A basic sliding block model incorporating friction was developed by Heim (1932) and subsequently advanced by Crosta (1991) and Erismann and Abele (2001). Pariseau and Voight (1979) and Körner (1977, 1976) developed velocity-dependent resistance models which were then coupled with a DEM by McEwen and Malin (1989). Crosta *et al.* (2003) call attention to two constraining assumptions associated with 2-D flow models, namely the two dimensional flow and constant physical mechanical properties of the failed mass. According to the authors, these assumptions are justified if the model is used to represent the average spatial and temporal condition of the channel, slope and moving mass over short distances. It is important to identify as precisely as possible the known or potential release areas which can subsequently be modeled as single failure masses. The authors discuss the difficulty of accurately modeling the deposition area based solely on the calibration of the model using previous runout distances. Thurber Consultants (1983 *in* Hungr *et al.*, 1987) used an approximate width-length ratio of 1 to 2 to model debris flow deposition areas along the Squamish Highway in Canada. According to Hungr *et al.* (1987) debris flow deposits can be mapped by taking into account the influence of topography and assuming a mean deposit thickness of 1.0 to 1.5 m for debris flows with volumes between 10,000 and 50,000 m^3. This correlates well with work carried out by Innes (1983). Through numerical modeling and statistical analysis of well-documented historical landslides, Legros (2002) critically challenges the status quo regarding the mobility of long-runout landslides. Legros (2002) convincingly demonstrates that only the presence of water within the failed mass could reduce the internal coefficient of friction enough to allow the landslide to runout much longer than would normally be expected. Furthermore, he discards the coefficient of friction (ratio of the fall height to the runout distance) as meaningless in predicting runout distance and instead demonstrates that the shape of a landslide deposit is more accurately predicted using an estimation of the total debris volume and topography.

It is well documented that the length of motorable roads in the Indian Himalaya has increased significantly since the early 1960's (Sah and Mazari, 1998) and the increase in the exposure of these roads to landslide hazard is examined by Haigh (1984) for a short section of the Mussoorie – Tehri road in Uttarakhand. Haigh (1984) developed a technique to predict the scope of the required landslide clearance operation based on a relationship between landslide frequency and magnitude which relies only on an accurate measurement of the release scar width in order to arrive at an accurate volume estimate. Although the author realizes that this semi-log-linear relationship probably varies from location to location in response to changes in rock-type, climate, and age of the road, and must be calibrated with empirical data, "It (nevertheless) opens up the possibility that hill-road clearance operations (and hazards mapping of potential run-out zones) can be evaluated by remote sensing" (Haigh, 1984, p. 75). Gupta (1997) presents an inventory of damages sustained by roads in the Himalaya due to various natural processes including landslides, flash floods, cyclones and earthquakes over various periods of time upto several hundred years ago. The author concludes that little can be done to prevent future disasters from occurring, rather more effort should be placed on effectively mitigating their severity, frequency and size by careful planning through the application of hazard-zoning maps, increasing public awareness especially in vulnerable areas, establishing a global hazards database for use by all countries and the establishment of an accurate natural hazard prediction and warning system.

In the case of most medium-scale hazards mapping projects, time and resource limitations prohibit detailed, site-specific investigations of individual landslides or debris flow channels. Under such circumstances, including the present project, heavier emphasis may be placed on calibrating the run-out model using known or previously established deposition areas and incorporating frictions based on slope, aspect and run-out distance derived from a DEM with an appropriate spatial resolution (McDougall and Hungr, 2004; Crosta *et al.*, 2003). The model developed here and described in more detail in Chapter 3, relies on the identification of a release area (Crosta *et al.*, 2003) and potential initial volume of material (Legros, 2002; Hungr *et al.,* 1987) and models the potential deposition area based on topography (Legros, 2002; Ghilardi *et al.,* 2001) and terrain friction (Pistocchi *et al.,* 2002). Calibration of the model to 6 known landslide and debris flow sites identified in the field was accomplished over several iterations on a trial and error basis.

An important consideration which is attracting more attention is the uncertainty and variability inherent in the input factors used in hazards mapping in general and susceptibility mapping in particular because of its often quantitative nature. The uncertainty in qualitative maps which is based solely on the interpretation of an expert is much higher and more difficult to evaluate than the variability of errors in a map generated using quantitative techniques. Variability may first be introduced into a typical hazards analysis with the imprecise delineation of landslide release areas identified in the field, on air photos or extracted from an existing inventory map or database. The comparison of multi-temporal inventory maps or the creation of activity maps also introduces uncertainty owing to the often different techniques and equipment used to identify the sites and the subjectivity of the different researchers. The extraction of information from parameter maps for landslides also results in errors due to spatial variability (e.g. range of slope gradients expressed as a mean value). Simple geomorphological modeling of runout zones requires, at the very least, accurate input maps of slope gradient, aspect, and land use/cover each of which are affected by variability due to differences between the values assigned to each pixel on the map and the actual value measured on the ground (Mantovani *et al.*, 1996). The numerical and/or logical combination of multiple input maps within a GIS in order to arrive at a final hazards map often exacerbates the errors, uncertainty, and variability inherent in the input data, yet these errors are rarely considered due to the lack of ability of most GIS programs to automatically track them (Irigaray *et al.*, 1996). Increasingly, however, this problem is being addressed by analyzing the required data in a statistical software package external to or loosely couple with a GIS. A Monte Carlo simulation, for example, allows for the computation of the variability of the output based on a natural or predetermined range in the input data (Hammond *et al.*, 1992). Haneberg (2001) proposes combining process-based models with parameter variability and uncertainty in order to come up with a rational probabilistic approach to landslide hazard assessment. The advantage of this method is that the inherent variability of each input parameter is input into a mechanically based model of slope stability at the start. The inclusion of a statement of uncertainty or variability in a hazard map serves two very useful purposes. First, it allows the analyst to gauge the quality of each input source by quantitatively assessing its specific contribution to the variability in the final hazards map. For example, if the range in error in one of the input maps is found to exceed the variability in the output data then the results of the analysis will be of limited use. Second, a statement of variability or precision will help other researchers to determine the quality of the map and extend its practicality over other maps for which the degree of error is unknown.

The utility of mass wasting maps as tools in land use management and development planning increases from inventory maps through to vulnerability maps. Vulnerability maps contain the most detailed information regarding mass wasting activity (i.e. location, frequency and magnitude) and the likely consequences for people and infrastructure (Bernknopf *et al.*, 1988; Einstein, 1988). An evaluation of hazards mapping and mitigation techniques used in China is presented by Tianchi (1994) while Rao (1997) states bluntly that "The present approach to landslide correction (mitigation) in India needs to be improved significantly" (Rao, 1997, p. 17). Following two and a half decades of research in the Himalaya, Rao (1997) addresses this need through a "National Strategy for Landslide Hazard Mitigation" which is designed to curb the increasing destruction of roads, bridges, dwellings, agricultural lands, forests, and human lives as a result of the ecological degradation of specific hill areas by human activity. The main strengths of this strategy are that it is a coordinated, multi-agency effort emphasizing the need for accurate and easily-available hazard zonation maps. It promotes the establishment of a national landslide databank containing "All information concerning landslides and their occurrence, the damages arising therefrom, relevant geotechnical and geological data, and other related information…compiled on a systematic basis" (Rao, 1997, p. 19).

Ives and Messerli (1981) identified a need to evaluate new "…methods for assessing and mapping mountain hazards and slope instability for application to land-use decision making in Nepal in particular and tropical subtropical mountain regions in general" (Kienholz *et al.*, 1983, p. 196). This was addressed through the Mountain Hazards Mapping – Nepal project sponsored by the Nepal National Committee for Man and the Biosphere (Unesco-MAB) and the United Nations University (UNU). Input hazard zonation maps provided important information regarding the location and activity of various mass wasting and denudation phenomena and combined with land use, vegetation, and geology maps, they became useful planning tools for road alignment and design, location of a major utility, or general regional planning. The authors conclude that it's not possible to generalize the stability of the whole area, as pockets of both high and low activity are scattered throughout and that although rock fall and avalanche activity can at least partly be attributed to deforestation on south-facing slopes, the overall "…human influence on the hazard situation is estimated to be very low" (Zimmermann *et al.*, 1986).

1.2.3.3 Human Impacts

The final approach to hazards analysis focuses specifically on the various aspects of human activities and their role in altering the risk and hazardousness of a place. This approach goes beyond the simple evaluation of land use/cover change as a preparatory or triggering factor of mass movements and considers the history of human activity, current and future trends in land use/cover and planning and management policies and the direct consequences of these policies on the physical environment.

A review of the history of human impacts on slopes and associated natural processes in a given region provides a reference against which the impacts of future human activities can be gauged or measured and serves as a vitally important component in hazards research. Sah and Mazari (1998) noticed that during the early to middle parts of the 1900's, mass movements posed a negligible hazard and that the magnitude of most recorded events was relatively small. Since that period, the authors claim that the recurrence and intensity of mass movements has increased significantly and this increase in activity is mostly attributable to escalating socio-economic development including road construction, growth in tourism, and greater population pressures. The period between 1960 and 1980 saw a major increase in the length of motorable roads throughout much of the Himalaya. Road construction in the eastern sector was funded mainly by China, in the central, southern and western areas by India and in sections of the northwest by Russia (Zurick and Karan, 1999). Following the dramatic increase in accessibility, many valleys that were formerly detached from markets to the west, south, and east have since been opened to new economic opportunities and in some cases exploitation.

Research on the repercussions of this new era of land use/cover change associated with the increased attention from political centers in the south and abroad has mostly been carried out in small study areas (10's to 100's of kilometers squared) making extrapolations of results gained in these micro- to meso-scale regions difficult without explicit qualifications and severe limitations. Lithology, slope hydrogeology, vegetation cover and the presence of vertical slope faces or bluffs in unconsolidated material should all influence road alignment in mountain areas so as to avoid areas which are known or suspected of mass wasting activity including bank erosion (Sah and Mazari, 1998). Tucker (1982) points out that despite the increase in landslide activity due to the hasty construction of high-altitude roads through many Himalayan forests, many inhabitants viewed this as a necessary price for better accessibility to markets in the plains and improved strategic security in the region. In some areas like the Roshi watershed in Nepal, community-based forestry activities have contributed positively towards the restoration of forest quality as well as improving slope stability (Gautam *et al.*, 2002). Proper management of forests, both in terms of density and quality, can help to reduce landslide risk (Jordan, 1994), while Marston *et al.* (1996) found no direct link between deforestation and an increase in flood hazard in their study area in Nepal. Virgo and Subba (1994) carried out a 12 year land use/cover study over a 200 km^2 area in Nepal using air photo interpretation and extensive fieldwork. Their results indicate that despite a noticeable increase in population and a doubling of the area affected by landslides, the overall distribution of land use/cover has remained relatively stable with much of the change characterized by changes in the spatial distribution of land use/cover types. Schickhoff (1995) noticed similar trends in the forests of the Kullu Valley stating that negative structural changes within forest stands and along forest margins are perhaps more important than the conversion of forests into cultivated and grazing land in terms of hazards analysis. Furthermore, the author draws attention to the fact that internal changes to forest structure may not be as readily identifiable on air photos or satellite imagery, complicating the task of analyzing land use/cover change for the purpose of assessing its impacts on erosion and denudation processes. Nevertheless, following a thorough review of existing remote sensing techniques as well as new methods of monitoring land use/cover change and its effects on soil conditions, Sommer *et al.* (1998) concludes that remote sensing techniques show strong application to hazards research by allowing for the quantitative mapping and monitoring of land use/cover using time series analysis and providing input into ground validation and calibration models.

Gerrard and Gardner (2002) warn against using simplistic relationships between deforestation and land degradation, as much depends on the nature of deforestation and subsequent land use/cover. Their results agree closely with those of Sarkar *et al.* (1995) who found that most landslides occur on abandoned or improperly managed terraces (in terms of irrigation), in degraded forests and in barren lands with steep, unvegetated slopes. Blaschke *et al.* (2000) reached similar conclusions stating that surface erosion rates are greatly increased in agricultural areas characterized by excessive cultivation, overgrazing and repeated burning of vegetation. The consequences of inappropriate management of agricultural areas on hazards and risk thus become apparent, highlighting the need for careful planning and execution of land use/cover change policies in order to minimize the risk of soil erosion and to reduce the potential for mass movements. Oyarzún (1995) found that infiltration rate was mainly controlled by organic matter content and the bulk density of soil while silt percentage and permeability was controlled solely by slope gradient. Using a compound measure of soil erodibility, the author found erosion was highest in degraded areas and lowest in native forest lands where the soil profile remained in tact. Other authors suggest that in order to reduce the risk of landsliding, orchards/gardens should be converted to multi-layered forests or terraced to prevent soil loss (Zisheng and Luohui, 2004) and grazing should be discouraged on steep slopes due to risk of compaction which alters promotes surface runoff leading to more intense surface erosion (Suneja, 1977).

According to Singh and Roy (2002), the rapid pace of development has already altered the biophysical setup of the Kullu Valley, and Blaschke *et al.* (2000) claim that the impacts of mass movements on land productivity will increase over the next few decades mainly as a consequence of increasing populations expanding on to steeper and more marginal land in search of food, fiber and fuel. This will be further exacerbated by climate change resulting in more storms of greater intensity (Blaschke *et al.*, 2000). Froehlich and Starkel (1993) echo these findings stating that land use/cover changes have caused a disturbance in the equilibrium of slopes and river channels. Specifically, the authors blame the proliferation of debris flows and mudflows on steep slopes on the removal of a deep and dense root system, while slumps, falls and slides are occurring with increased frequency along road cuts.

An anthoropological review of the hazards situation in the Himalaya by Berreman (1979), points to the exploitation and consequent degradation of the environment by people who have little connection with the landscape. Tourism and mountaineering, specifically, have negatively altered the environment as well as the lifestyle and livelihoods of the local inhabitants to a certain extent (Berreman, 1979). The anthropogenic landscape of the Himalaya is aptly presented by Zurick and Karan (1999) who emphasize that cultural diversity cannot be divorced from the complex physical environment when attempting to decipher the geomorphology of the area. The ancient traditions of the people, who have inhabited these valleys for thousands of years, are undeniably fused with the natural landscape on which they are dependent for their very survival. Recent (since the 1960's) changes in population density, agricultural production methods, and the level of interest on an industrial and commercial level are rapidly altering the manner in which people are interacting with and using the land. While Zurick and Karan (1999) are cognizant of the dangers of extrapolating results from small study areas to larger regions, they do warn that in a number of key areas, human activities such as intensification of commercial agriculture and orchardry, construction of improperly planned roads, and development of hydroelectric infrastructure including dams and canals are stressing the physical landscape beyond natural dynamic equilibrium thresholds resulting in increasingly unpredictable adjustments of the slope profile to new quasi-equilibrium levels.

Chapter 2 Study Area Background

2.0 Introduction

The study area comprises the upper 256 km^2 of the Kullu Valley in Himachal Pradesh state. The Kullu Valley is drained by the Beas River and its main tributaries between the town of Bhuntar in the south and Rohtang Pass in the north (31.75° N – 32.50° N and 77.00° E – 77.25° E) (Figures 2.1 and 2.2). The Kullu Valley lies in the Kullu District, which is in the Indian state of Himachal Pradesh bordered to the north by Jammu and Kashmir, to the east by Tibet, Uttar Pradesh to the southwest and Haryana and Punjab to the southwest and west (Figure 2.1). Shimla is the state capital, while Kullu town, situated 10 km north of Bhuntar is the district capital. The main population centres are Bhuntar, Kullu, Raison, Katrain, Naggar, Jagatsukh, Manali and Palchan. District population was reported as 415,073 as of 2004 (http://hphealth.nic.in/yb2s19.htm) with close to 90% classified as rural. Accordingly, the population in the study area is estimated at over 200,000; approximately 18,306 in Kullu and 6,265 in Manali, the two biggest urban population concentrations (Kuniyal *et al.*, 2003; Census of India, 2001).

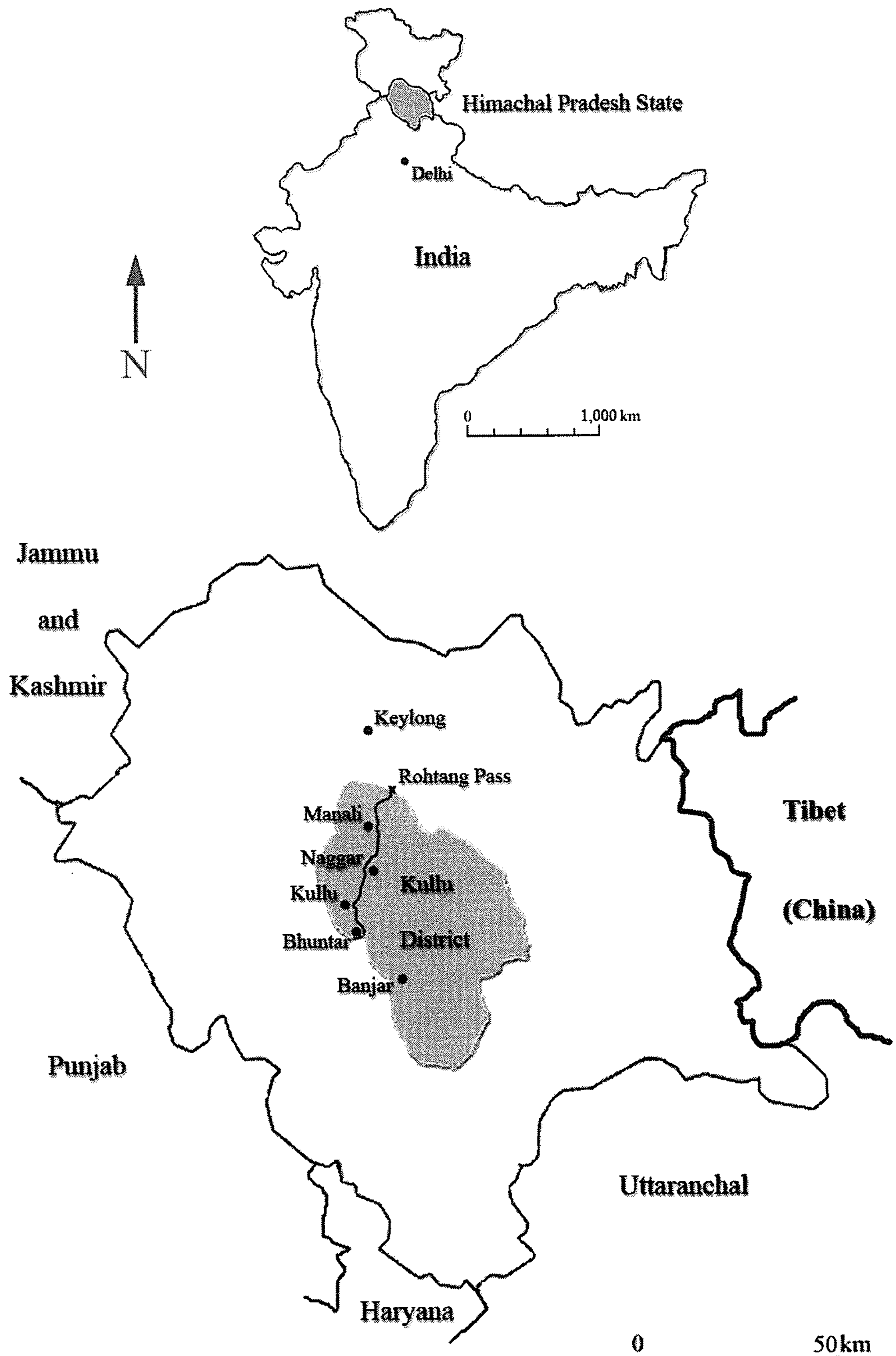


Figure 2.1 Kullu District in Himachal Pradesh State showing important locations. (Modified from Mapsof India.com © 2006 and Author)

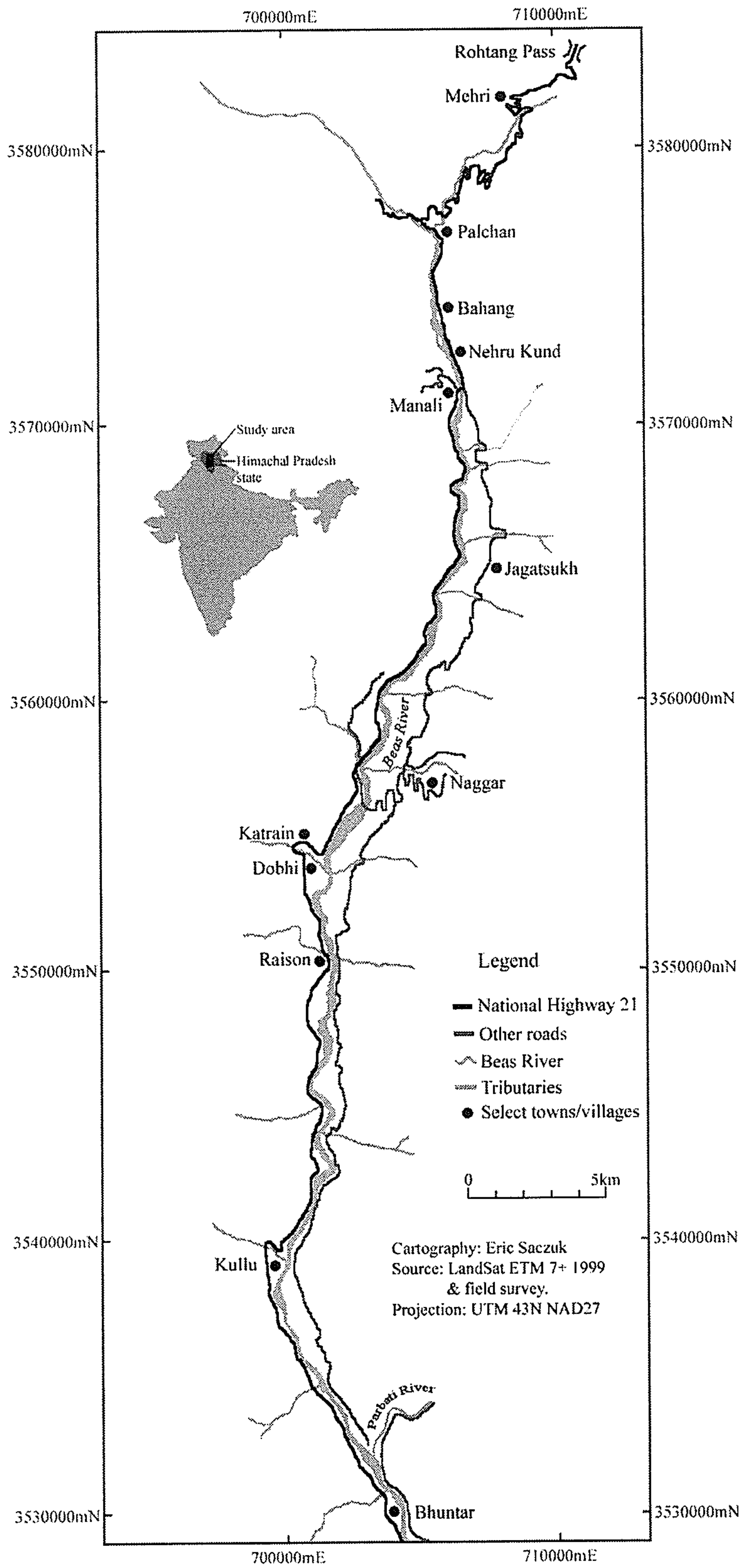


Figure 2.2 Study area along the Beas River in the upper Kullu Valley. (Author)

2.1 Physical Setting

Lying in the Pir Panjal mountain range, the transverse Kullu Valley is in the transition zone between the Lesser Himalaya and Siwaliks to the south and the Greater Himalaya to the north. Elevation of the valley floor rises northward from Bhuntar at 1,100 m to 3,970 m at Rohtang Pass with an average relief of ~1,500 m to the immediate valley slopes. The main summits, set back several kilometers, reach elevations over 6,500 m. The Beas River, a fourth order basin rising in Beas Kund lake at an elevation of 4,316 m, drains 66 watersheds before its confluence with the Sutlej River, a tributary of the Indus. Flowing in a general southerly direction, the catchment area of the Beas River within the study area is 2,800 km^2 with an average valley width of 1.5 km, reaching a maximum of almost 3 km near Katrain, where its meander loops impinge on the valley slopes. The main channel is incised into paraglacial fan deposits (Ryder, 1971) into which up to 5 levels of unpaired fluvial terraces 25 m – 30 m above the flood plain have been cut between Bahang in the north and Bajura in the south (10 km south of Bhuntar, Figure 2.2).

The river is characterized by heavy bedload comprised of coarse, bouldery material through which the main channel shifts laterally, as is typical of a high energy stream with a steep gradient and variable discharge (Gardner, 2002). Gross channel gradient between Rohtang Pass and Bhuntar is 0.4 m km^{-1}, with three distinct gradient sections separated by nick points at Mehri, Bahang and Dobhi, between which the channel gradients are 2.0 m km^{-1}, 0.8 m km^{-1} and 0.2 m km^{-1}, respectively (Figure 2.2). The nick points and fluvial terraces suggest frequent rejuvenation of the river and renewed downcutting due to continued tectonic uplift of the valley floor. A rock-bound gorge approximately 100 m – 200 m deep and 50 m wide located between Mehri and Palchan is a particularly noteworthy example of the vigorous incision of the Beas River into the valley floor. Frequent bank erosion occurs along most of its length, but it is more pronounced just downstream of Palchan near Bahang as the river exits the gorge and traverses onto a lower-gradient floodplain. Downstream of Dobhi, the river exhibits depositional characteristics as evidenced by a shift to lateral migration which results in the formation of terraces.

Much has been written and recorded about the flooding and associated death and destruction caused by floods on the Beas River and some of its main tributaries (Calvert, 1871; Gore, 1895; Tyacke, 1907; Forbes, 1911 *in* Gardner, 2002). More recently, a destructive flood swept down the Kullu Valley in September 1995, destroying roads, bridges and a few dwellings and causing 65 deaths near Kullu (Sah and Mazari, 1998; Tolia *et al.,* 1997). Based on research pertaining to changes in forest cover in the upper Beas watershed, Hofer (1993) noted that the annual range between low and high flows on the Beas River was decreasing and concluded that this was associated with an increase in forest cover upstream. Much effort has been expended in an attempt to reduce risk posed by floods through engineering works including installation of deflection bars, reinforcement of areas prone to bank erosion using gabion baskets (Figure 2.3), diversion of sections of the Beas River and a few tributaries away from flood-prone areas, and the relocation of some infrastructure (e.g. a grade school near Bahaang).

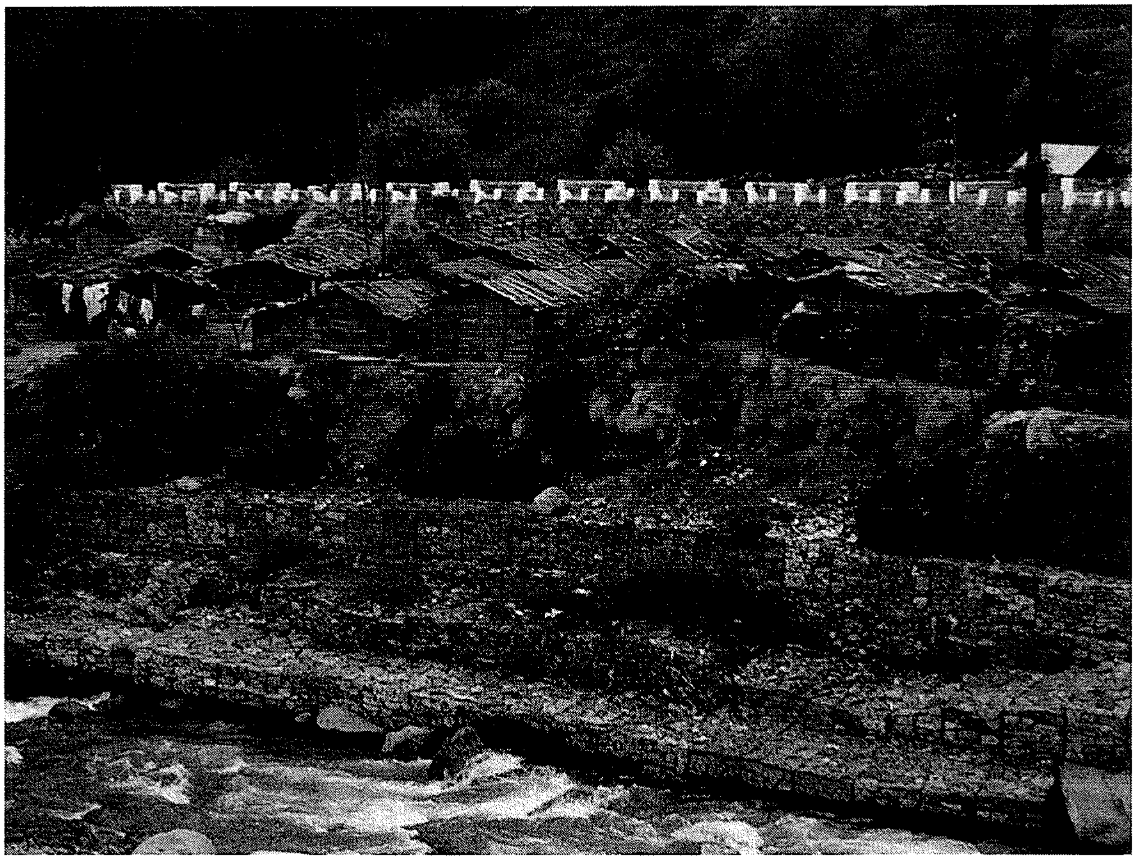


Figure 2.3 Bank reinforcement measures along Beas River near Dobhi. Note location of NH 21 above dwellings. (Author, July 1999)

2.1.1 Geology

The Himalaya is representative of a rare subductive tectonic zone where the Indian continental plate is continually being thrust northwards under the Eurasian continental plate, with a resulting estimated shortening rate of 6 – 16 mm y^{-1} (Kayal, 2001) over the past 50 million years (Molnar *et al.*, 1993; Zhao *et al.*, 1993). This continued collision has resulted in some of the highest rates of vertical uplift anywhere in the world on the order of 5 mm y^{-1} (Pannikar and Subramanyan, 1996). The study area lies mainly within the Higher Himalayas Metamorphism tectonic features and is geologically composed of predominantly Precambrian crystalline metamorphics including phyllites, schists and gniesses, and igneous rock such as granite (Sah and Mazari, 1998). Two heavily folded and faulted thrust sheets comprised of meta-sedimentary sequences of shales, quartzites, sandstone and dolomites with a common tectonic history, but differing in the grade of metamorphism, intensity of deformation, and lithology (Virdi, 1979 *in* Sah and Mazari, 1998), are present in the southern areas of the valley (Mehta, 1976). Together these two thrust sheets, namely the Chail and Jutogh, form a recumbent fold with a tear fault showing signs of dextral movement of 1.5 km along a thrust contact aligned with the Beas River (Shankar and Dua, 1978 *in* Sah and Mazari, 1998). The high degree of fracturing and deformation of the rocks renders them structurally weak with the Chail demonstrating schistosity while the Jutogh displays typical slaty cleavage (Sah and Mazari, 1998). Frequent rockslide activity is closely associated with slopes where resistant quartzite or sandstone is interbedded with weaker shales or mudstones. In instances where the resistant components are significantly thicker, wedge failure may occur whereas if the reverse situation is true (the weaker beds are thicker), the area becomes more prone to rotational slumping (Deoja *et al.*, 1991) due to the potential for significant deformation of the less resistant material.

This combination of rapid tectonic uplift, high vertical relief and associated potential energy, weakened geologic structure, and the presence of numerous faults and lineaments predisposes the Kullu Valley to frequent slope failure and mass wasting activity. This environment has contributed to an estimated denudation rate of several mm y^{-1} (Owen *et* *al*., 1995b; Burbank *et al*., 1996). The triggering mechanisms including earthquakes and climatic factors are discussed in greater detail below.

2.1.2 Seismicity

Frequent seismic activity continuously reshapes the morphology of the area through the initiation of landslides, rockfalls, and other slope failures triggered by earthquakes. Major (M >7.0) earthquakes have been recorded in and around the Kullu Valley in 1905, 1963, 1991, 1997 and 2000 (Lall, 1995), while moderate to strong magnitude events (M ~6.0) occur up to several times a year in the region. Earthquakes cause sudden lateral and vertical accelerations of the earth's surface in the affected region of up to several g which alter the balance between forces that resist movement and forces that promote movement of slope material. In instances when acceleration parallel to the slope or plane of failure is sufficient to overcome frictional forces, the land mass will slide down slope. Earthquakes in the Kullu Valley tend to be shallow (≤40 km focal depth) and closely associated with the tectonically active Main Boundary Thrust (MBT), which separates the Lower and Higher Himalaya as well as two prominent tear-faults (Kayal, 2001). A number of recent, moderate earthquakes recorded in the vicinity of the Kullu Valley in 1991 (M 6.5), 1996 (M 6.9), 1999 (M 6.6) and, 2002 (M 6.3) caused significant loss of human life due to major landslide activity (USGS, 2005, Narula *et al*., 2000; Geological Survey of India, 1993; 1992). Landslides triggered by earthquakes in the Kullu Valley tend to be closely associated with roadcuts, particularly those above treeline, suggesting that potentially unstable slopes are more prone to failure by this triggering mechanism.

The first Indian-based seismic observatory was established in Calcutta in 1898 and the current nation-wide network consists of 60 mobile and permanent stations (Figure 2.4). Despite this, many earthquakes that occur in the Himalaya are recorded by sensors outside of India (Kayal, 2001). One of the main reasons for this is that only 20 observatories have been upgraded to global standards (i.e. STS2-Q680 or CMG 40T-72A) (Kayal, 2001). Specifically in the northwest Himalaya, the Wadia Institute of Himalayan Geology (WIHG) and the University of Roorkee operate a few seismic stations established in the 1990s. In addition, five to eight temporary microseismic stations were operational in the Parbati Valley in 1978 and 1979. These stations recorded about 500 microearthquakes with a dense cluster located around 32° - 33°N and 76° - 77°E (Kayal, 2001) just west of the study area indicating that the area is subject to high concentrations of tectonic stress.

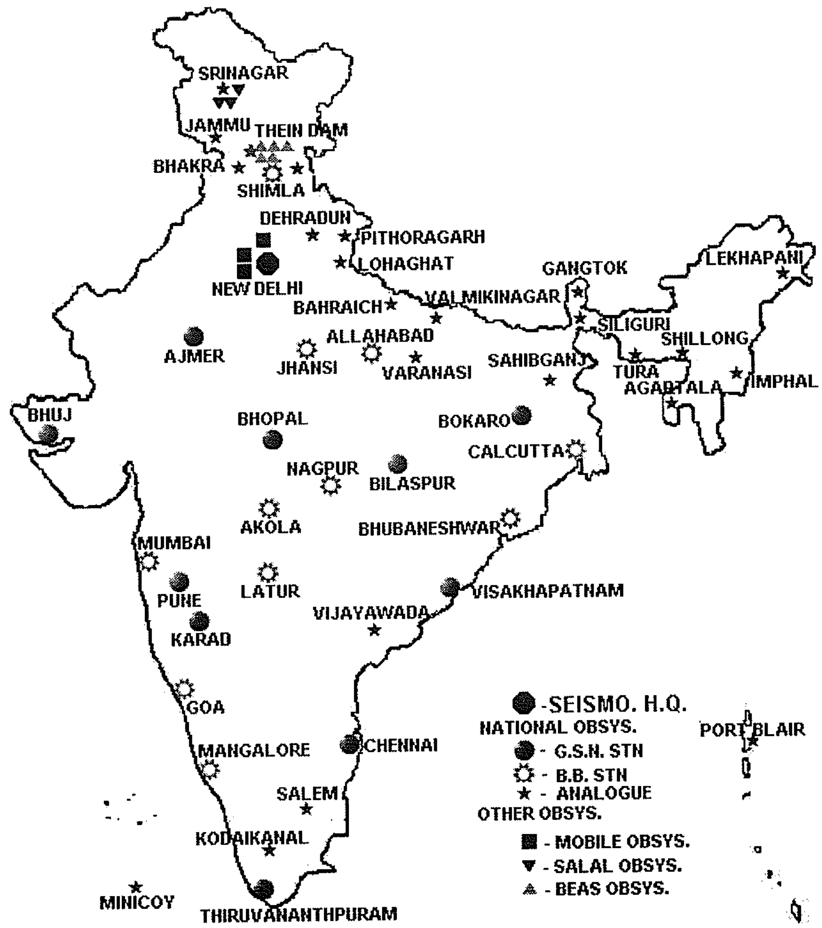


Figure 2.4 Network of seismological observatories in India. (www.imdmumbai.gov.in)

The limitations and inconsistencies of the seismic record, which are discussed further in Chapter 4, for the Himalaya in general and the Kullu Valley in particular, make it difficult to accurately determine the trend in seismic activity for the region over even the past several decades. The lack of permanent stations in close proximity to the study area, the increasing number of permanent and temporary stations and the changing (i.e. improving) standards of those stations, introduces significant bias into a temporal analysis of earthquakes (see Figures 4.15 and 4.16). The main problem stems from the fact that more, lower magnitude earthquakes are being detected as more stations are installed and upgraded to better standards. This can be overcome to a certain degree by considering only strong earthquakes (i.e. $M > 6.0$) which are large enough to be detected by all types of seismometers (Figure 2.5). The drawback to this is that smaller earthquakes that are capable of initiating slope failures would be ignored which is particularly problematic because according to Kayal (2001) the number of earthquakes increases 10 fold with a decrease in magnitude of 1.0. A statistical analysis of the available earthquake record for the period between 1882 and 2004 is presented in Chapter Section 4.3.2.

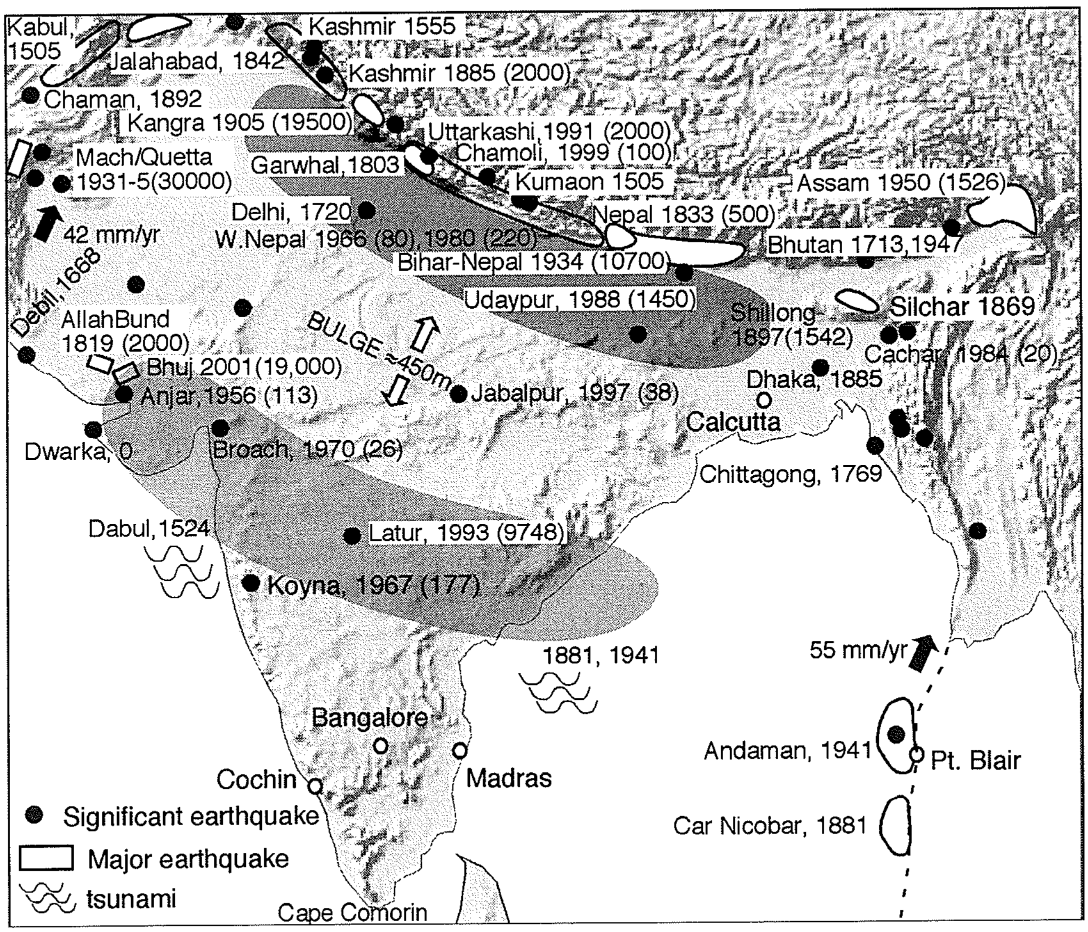


Figure 2.5 Epicentres of significant and major earthquakes in India from 1505 to 2001 and cross-section showing a schematic view of Indian tectonics. Gray areas show regions of heightened seismic activity within India. (Bilham, 2004 with permission)

2.1.3 Glacial, Alluvial and Mass Movement Deposits

Evidence of prior glaciation in the area includes the broad, asymmetrical U-shaped cross-section of the Kullu Valley, morainal deposits exposed by roadcuts in the upper portion of the study, and many large paraglacial debris flow fans. 277 alpine glaciers currently occupy some of the upper summits of the Beas catchment, with the largest being Sara Umga with a surface area of 56 km^2 (Sangewar and Shukla, 2003). The maximum historical southern extent of the glaciers is uncertain, but a cursory examination of road cuts along NH 21 and the east-bank road, revealed a distinct change in the characteristics of deposits along a north to south transect. Angular boulders embedded in a fine-grained matrix interpreted as till, appear to be more prevalent in the northern parts of the valley. In the south, colluvium and paraglacial debris flow deposits appear to be more common at least near the surface. This observation suggests that the main valley glacier did not extend much further south than approximately Kullu, however this hypothesis would have to be confirmed through further field investigations.

Following deglaciation (≈10,000 y B.P.), large, low gradient, debris flow fans of glacial and glacio-fluvial origin were deposited, and presently overly the metamorphic rocks forming 120 – 200 m-high bluffs along the Beas River (Figure 2.6)

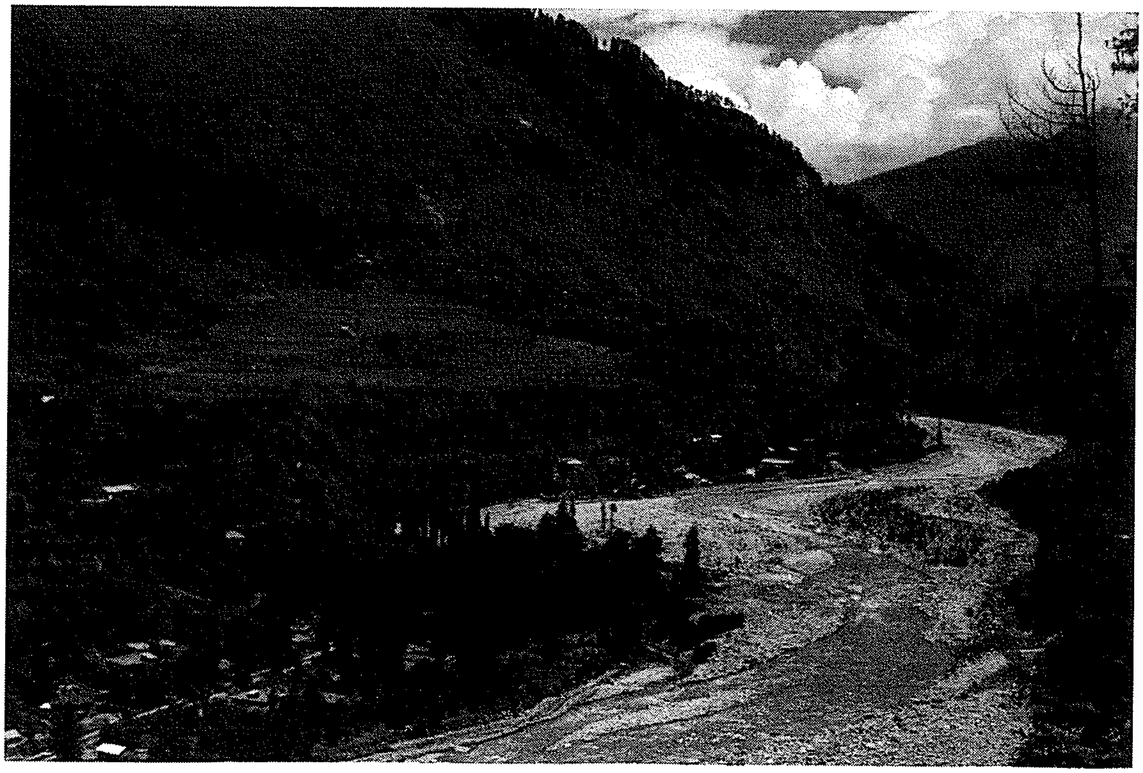


Figure 2.6 Cross-section of Beas River looking north, showing smaller, low-gradient glacio-fluvial fans along the west bank and steep bluffs along the east bank. (Author, August 1999)

The fans are an inherent part of the asymmetrical cross-section of the Kullu Valley. Larger fans have formed along the east bank of the River due mainly to slightly wetter conditions associated with aspect and the circulation of the monsoon. Geology also exerts strong structural control on the area due to the presense of a thrust fault aligned more or less with the Beas River which has rendered the east-facing slopes much steeper than west-facing slopes. The distal fan extents form steep bluffs which are frequently undercut and eroded by river action resulting in ongoing mass wasting at the fan toe (Figure 2.7). Fan profile above the bluffs is generally concave upward and steep (over 20°) with a concave upper slope of about 16° which abuts the main rock slopes rising at a constant angle of about 35° to the upper part of the catchment basin which is steep (over 40°) and concave.

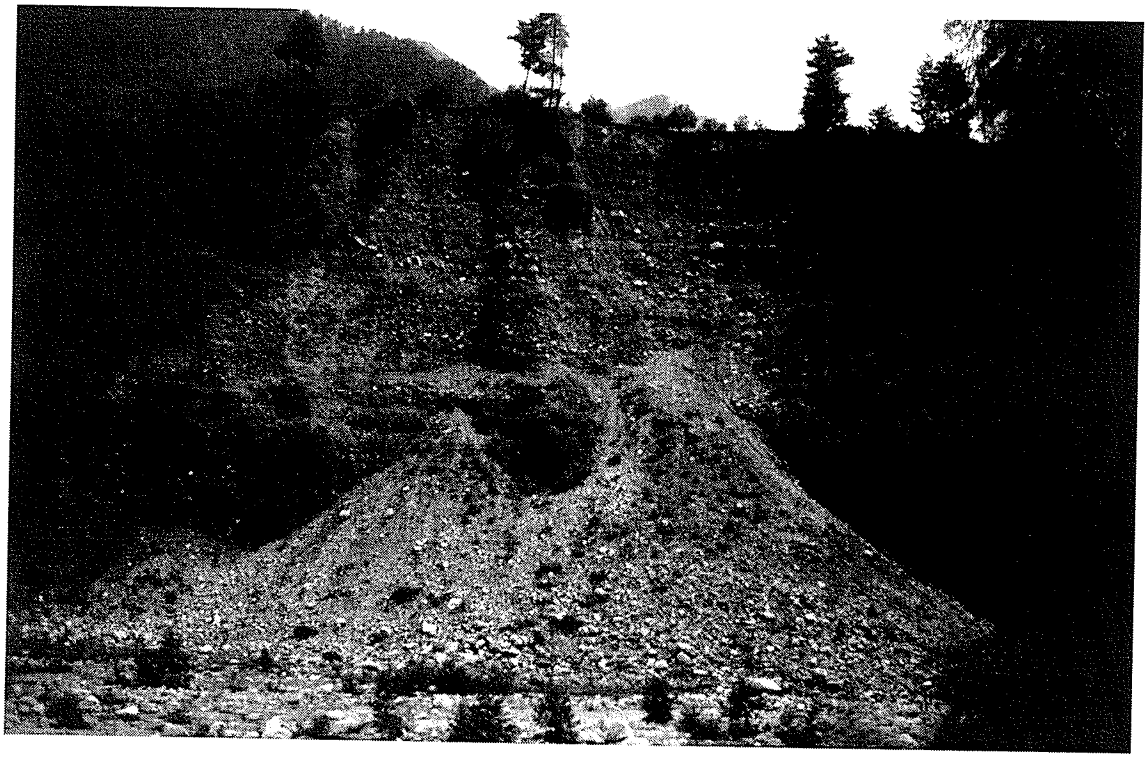


Figure 2.7 Flooding and subsequent bank erosion leads to frequent undercutting and failure of the already steep fan toe. Beas River is at the bottom of the photograph. (Author, June 1999)

For most of its length, NH 21 between Bhuntar and Manali, is situated at base of the smaller fans along the right (west) bank of the Beas River immediately adjacent to its flood plain. North of Manali, the highway is positioned higher up the slope and away from the flood plain except at crossing points. A secondary highway located for most of its length on top of the larger fans along the east bank connects NH 21 at Manali with towns and villages along the east bank including Jagatsukh and Naggar. Numerous instances of mass wasting activity including rock fall, slumping, landslides and debris flows were recorded along both highways and several other minor roads in the study area between June and August of 1999 and 2000. The alignment of the road (either at the base or on top of the paraglacial fans) does not seem to affect the predisposition of these slopes to various processes of denudation and erosion.

Intense physical weathering, particularly in the alpine zone above 4,000 m elevation, is the primary agent of erosion. Chemical weathering plays a minor role on lower slopes. Materials loosened by weathering are transported downslope by mass wasting activity in the form of landslides, progressive failures, debris flows and torrents, surface wash, and rock fall as well as flooding. Several high magnitude landslide, debris flow and flood events can be observed in the landscape and have been recorded literature (Civil and Military Gazette, 1894; Owen *et al.*, 1995b). In addition, there is evidence of large contemporary mass movements such as, for example, the progressive failure on the lower slopes across the Beas River from Manali near Nehru Kund (Figure 2.2). More recently, attention has been focused on the activity of smaller but spatially and temporally more frequent erosion events (e.g. Gardner, 2002 Barnard *et al.*, 2001; Sah and Mazari, 1998; Hearn and Jones, 1987). A state of dynamic equilibrium, characterized by long periods of spatio-temporally frequent, low magnitude erosion activity, punctuated by shorter episodes of high magnitude denudation at specific sites, prevails in the study area

Lower magnitude events represent perhaps an even higher level of risk to people and structures in the area than high magnitude events, because the smaller volume of material mobilized and their recurrence rate tend to be underestimated or outright ignored. In a number of documented cases, this has had tragic consequences. This is exemplified by Sharma vs. State of H.P. and others (1996) where a resort situated on the west bank of the

Beas River was washed away during a low-magnitude flood event exacting a serious human and economic toll. This high profile case drew attention to the inadequacy of the existing zoning laws and their enforcement as well as to the effects of attempting to alter the course of the main channel of the Beas. These zoning laws do not apply to the construction of roads, which, in mountainous environments are generally associated with more frequent mass wasting activity due to removal of toe support and over-steepening of rock slopes. Many roads in the Kullu Valley, especially the switchback stacks in the upper reaches of the watershed, are subject to frequent and widespread landsliding and surface wash, exacerbated by the lack of substantial vegetation above the tree line of 3,500 m. The roads and highways between Bahaang and Bhuntar, especially NH 21, are exposed to frequent inundation and pronounced bank erosion during spring melt and the monsoon (Figure 2.8).

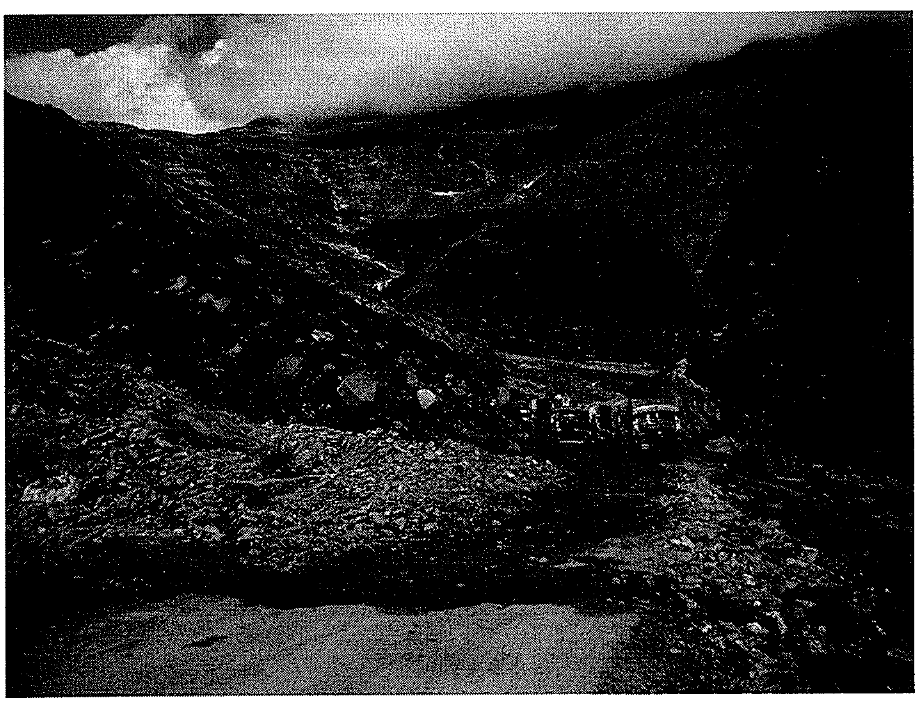


Figure 2.8 Frequent mass wasting activity affects traffic flow along NH 21, particularly above the tree line at 3,500 m altitude. (Author, July 1999)

Alluvial deposits are mainly confined to the river valley bottoms with paraglacial fans flanking the larger streams. Colluvium can be found in pockets throughout the study area often on the upper slopes, overlying older deposits along river valleys or deposited on top of the paraglacial fans. As mentioned above, till is exposed in road cuts at lower elevations and blanketing slopes in the upper reaches of the watershed towards Rohtang Pass. The sub-montane podsolic soils are generally thin on steep slopes and are characterized by moderate acidity, high iron and carbon content and a loamy texture with average depths of 50 to 100 cm (Singh, 1992). Due to a lack of nutrient and mineral constituents, the soils found here are considered generally unfavourable for agriculture (apart from the alluvial fans); however it is being increasingly used for horticulture with the aid of scientific and technical knowledge (Mittoo, 1978).

2.1.4 Land Use/Cover

The present land use/cover in the study area is comprised of Forest (43%), Agriculture (22%), Clearings (25%) and Settlements (10%). Agriculture encompasses all areas of private and commercial farming including fields where sparse orchard trees are intermixed with crops. Clearings are comprised of scrub, grass, grazing, open and abandoned land and all other areas that are generally devoid of trees and not regularly managed or modified. Forest encompasses all protected and reserve forests, forest plantations, and dense orchards. All human-built infrastructure excluding roads and bridges were amalgamated into the Settlement land use/cover category. Areas of alpine tundra, exposed rock, glaciers and snow near the ridges and summits were excluded from analysis as they are not subjected to the same forces of land use/cover change that affect the other categories. In addition, these areas rarely impact changes in hazards in the Kullu Valley.

Most settlements and agricultural fields are located on or near the relatively flat valley bottom or on nutrient-rich alluvial soils of the extensive paraglacial debris flow fans. Towns, villages and most other infrastructure tend to be situated along the main roads and highways in typical ribbon fashion, characteristic of many mountain areas. The proximity of settlements to the transportation network in the valley is at the same time efficient and risky, as much of the mass wasting activity occurs on slopes adjacent to roads, as discussed previously in Chapter 1, section 1.2.1. As is well documented in previous literature (e.g. Temesgen *et al.*, 2001; Sarkar *et al.*, 1995; Rawat and Rawat, 1994), the spatial and temporal frequency of shallow slope failures tends to be highest on deforested or degraded slopes followed by improperly maintained agricultural fields. Lowest frequencies are associated with mature, natural forest areas. Roads and other associated infrastructure often serve to exacerbate mass wasting activity in the land use/covers mentioned above.

Subsistance crops such as wheat and maize are grown on the lower slopes, whereas barely and rice are found on well-maintained terraces higher upslope mixed-in with pockets of temperate forest. Farther up slope, commercial orchard terraces are typically situated on previously abandoned land or less productive soils of the mid-slopes. Fruits commonly grown here include apples, bananas, oranges, olives, pears, peaches, apricots, cherries, plums, grapes, lichi, pomegranates and mango (Chib, 1977). Himalayan coniferous forests interspersed with grazing areas and open meadows blend into a mix of coniferous/deciduous forest beyond the orchards, up to the climatic tree line at approximately 3,500 m elevation. Areas under commercial agriculture tend to be more closely associated with soil erosion and landslide activity than subsistence crops or forested areas in the Kullu Valley.

Agriculture and to a lesser degree transhumance animal husbandry constituted the main economy of the area since the beginning of habitation in the Kullu Valley until very recently (Noble, 1991; Saberwal, 1999). Although agriculture is still the dominant economic activity, employing close to 80% of the population in various capacities, other employment opportunities have recently began to dramatically shift the economic focus of the area. Several land redistribution schemes initiated by the government in the 1950s and 1970s provided an opportunity for landless people to own and occupy land previously regarded as wasteland near existing villages (Gardner, 2002). These lands along with other traditional farms became part of the growing horticulture industry based primarily on apple orchards first introduced into the region in the late 1890s by British settlers (Banon, 1952). The construction of the first all-weather highway (NH 21) in the 1970s also had an important economic impact on the the Kullu Valley by linking it with other populated regions to the north (Lahaul, Spiti and Ladakh) and south (rest of India). A more detailed history of the settlement and development of the Kullu Valley is given in Section 2.2 below.

2.1.5 Weather and Climate

According to the Köppen-Geiger climate classification, the region is dominated by a highland Cwa regime characterized by warm, temperate, rainy conditions with dry winters and hot summers. Physiographically the Kullu District falls into the humid sub-temperate zone with temperatures ranging from an average low of between –15° C and -2° C in December to average highs of 15° C to 35° C in July (Singh, 1989). At the valley floor, average annual precipitation shows high inter-annual variability but a general figure of 1,500 mm is often used with as much as 90% of the annual precipitation falling as rain during the monsoon between June and late September (see Section 4.3.3).

Northern India's monsoon climate is strongly modulated by the Himalaya, particularly the south-facing slopes of the range (Barros *et al.*, 2004). The annual influx of warm, moist air originating in the Bay of Bengal brings persistent rains and significant convective storm activity to the study area. Topography plays a key role in modifying the local climate with a general decrease in temperature and an increase in precipitation on higher, north and northeast-facing slopes of the Lesser Himalaya up to 3,000 m. Micro-topographic and diurnal variations further alter this pattern on a very localized scale with some isolated peaks and ridges receiving an order of magnitude higher precipitation amounts than surrounding areas. Sah and Mazari (1998) note that the Kullu Valley has experienced a warming trend (although the time period is not specified), which has created a more moist regime, particularly on the lower slopes.

The effects of precipitation and rapid melt events on slope stability have been well documented in the literature (e.g. Chen and Lee, 2003; Shroder Jr., 1998; Wieczorek, 1987; Starkel, 1972a). Based on studies throughout the mountain regions of the world, most researchers agree that an increase in soil moisture leads to an increase in mass wasting and denudation activity (all other factors being equal). Following precipitation, either snow or rain, or the melting of snow or ice, water will pond in surface depressions, run off of slopes, seep into the soil by infiltration and percolation, raising the water table, add to the discharge in rivers and generally raise the potential for the transport of erodible material downslope. Long or short-term changes in precipitation and temperature can alter the geomorphic dynamic equilibrium of an area on a local, regional or global scale. Despite attempts by numerous researchers to quantitatively establish definite intensity or duration thresholds for precipitation events, or define antecedent moisture conditions that will certainly lead to failure, it is still very difficult to predict how much moisture is required in a specified period of time to initiate slope failure or a debris flow. What is known is that extreme precipitation events (in terms of either intensity and/or duration), very rapid snow or ice melt and higher soil moisture tend to promote slope instability and may trigger failure. Annually, numerous shallow landslides (<1 m depth), debris flows and floods are triggered in the Kullu Valley following particularly prolonged or heavy rain events, especially during the monsoon months of July, August and September.

2.2 Cultural Setting

Archaeological evidence found in Uttar Pradesh, Jammu and Kashmir and Himachal Pradesh states indicates that this part of the western Himalaya has been inhabited since at least the Stone Age (8,000 BC). During the past 10,000 years the region has been subject to numerous influences and incursions, most notably the Aryan push south from Asia in approximately 2,500 BC. There have also been infiltrations into the mountains by aboriginals from the southern plains, imposed British colonialism and most recently, unparalleled urban development driven by global economics. Zurick and Karan (1999) have identified five distinct historical phases, which according to the authors, have shaped the Himalayan Mountain landscape. These are; "...the prehistoric period of indigenous land settlement coupled with cultural invasions and early political conquests; the medieval period of early state formation under the feudal arrangements of the Rajput princes from India; the colonial spheres of influence; the era of post-colonial nationalism; and the modern period of national development and native land struggles" (Zurick and Karan, 1999, p. 65-66). These five periods reflect distinct shifts in how land is used, managed and administered, and provide a context for further analysis of the effects of land use/cover change on the susceptibility of the people in the study area to natural erosion processes.

2.2.1 Initial Settlement (10,000 BC – 1,400 AD)

According to ancient Tibetan religious texts, early Buddhists cut giant gorges into the mountains to aide in the removal of runoff from ancient Tibet, and powerful deities inhabited the lofty snow-clad peaks (e.g. Mount Kailas) forming a genuine connection between the heavens above and the earth below. Although these myths correspond to some degree with geological records, perhaps more significant is the apparent sanctification of the landscape and the association of natural processes with spirituality by Buddhists, and the intimacy that appears to have existed between people and the surrounding environment. The original inhabitants were mainly nomadic herders or people who divided their time between subsistence agriculture and livestock grazing until about 1,500 BC. The caste system in this area of the Himalaya began to emerge slowly around the 6^{th} and 7^{th} centuries AD, following the initial encounter between migrants moving north from the Indian plains and the resident khasa tribes of Aryan decent. The khasa tribes had already established a social hierarchical structure subsequent to their amalgamation with the original inhabitants in the area, who are themselves linked to the pahari and dom people of today. As early as 500 BC some of the land was being administered by the khasa people with individual villages tilling the land and taking economic responsibility for it.

Fire was used extensively as a management tool with the main land use activities being slash and burn agriculture, foraging, livestock grazing and hunting. In some areas of the northwestern Himalaya, the local inhabitants were required to pay tribute to the ruling elite in the form of medicinal products, game and timber, which put significantly more pressure on the valley ecosystems. Overall, however, land pressure was relatively low due to the small population numbers.

2.2.2 Historic Period (15^{th} – 19^{th} century)

Following the rise to power of the Rajput princes throughout most of the Himalaya in the 14^{th} and 15^{th} centuries AD, land use intensified significantly in many areas, particularly in the eastern Himalaya. The Rajputs afforded the peasant farmers security and an acceptable standard of living in exchange for a continuous supply of natural resources and products extracted from the seemingly endless inventory of the mountain environment (Harcourt, 1869). The pattern of exploitation of Himalayan resources continued with the subordination of the Rajput princes in the western mountains to the Mughal emperors in the plains, although for the most part the latter were content as long as the required timber and tribute was being supplied as requested. In the central and eastern mountains, the Rajputs were conquered by the Shah Kindgom of Gorkha beginning in the 17^{th} century. The Gorkha who saw the territorial ambitions of China towards Tibet and the British towards India as a threat, successfully united a 1,500 km stretch of the Himalaya, from Garhwal to Sikkim. The process of unification was sometimes peaceful and sometimes bloody but the effects it had on land use and the Himalayan landscape were nearly devastating. Although the goal of the Gorkha and Mughals, like the Rajputs, was to accumulate wealth and power through heavy taxes and exploitation of the environment and labor force, the highly centralized structure of the government added an extra level of disconnectedness. This put tremendous pressures on certain areas which previously were at least recognized by the local rulers as being fragile or unable to sustain the demands placed on them (Tucker, 1982). As will be discussed in more detail later in the chapter, this is one of the main problems facing the Himalaya today. Under a crippling 50% tax burden, lack of any guarantees against a poor harvest, the threat of eviction if unable to pay the high rents, and large loans with interest rates of 50% or more, many farmers simply were not able to cope. Perhaps even more destructive in terms of the effects on the landscape was the demand that all open lands be converted into agricultural fields in order to increase revenue and production. To facilitate this, peasants were offered direct incentives such as ownership of the land following an initial period of tenure to convert forests to cultivated land, which greatly accelerated the already rapid pace of extraction and clearing throughout the Himalaya. Eventually, land ownership returned to the individual farmer albeit not necessarily to the original farmer of a particular plot. This led to increased population growth and expansion of family-run farms during the late nineteenth and early twentieth centuries, blending into the British Colonial period beginning in the early nineteenth century.

2.2.3 Colonial Period (19^{th} – mid-20^{th} century)

The defeat of the ruling Gorkhas by the British military in Nepal in 1815 ushered in an era of Colonialism in the Himalaya. The next step for the British was to swiftly establish an unambiguous northern boundary to their expanding Indian empire in order to primarily gain control over the lucrative trans-Himalaya border trade routes and secondarily to exploit the apparently abundant mountain resources including minerals, timber, and commercial agriculture. This task required an incredibly ambitious survey of some of the most rugged and inhospitable mountain terrain on earth. The great survey of northwestern India was completed by the late nineteenth Century and provided the British with topographic maps of the routing through and resources of this remote yet strategically and economically important part of the Himalaya. It is reported that as early as the 1770's, the forests of several western Himalaya valleys were extensively cut to provide fuel wood and construction materials to the colonialists who were constructing railways, roads and generally settling the area. It was soon realized that in order to maintain the high rates of timber extraction (close to a million cubic meters annually in the neighboring valleys of Kuman and Garwhal in the mid-1880's), some form of silviculture would have to be introduced into the region. This, in turn, required a restructuring of the existing local forest policies and management practices and a shift in jurisdiction over the forest resources away from indigenous users such as traders and villagers and into the hands of the British-controlled Forest Department as per the Indian Forest Act of 1865. The Forest Department took over exclusive revenue rights from timber and related products extracted from New Reserves which came into being following the reclassification of forested lands by the British in the mid-nineteenth Century. This reclassification effectively banned traditional local users from forests that they had been locally managing for Centuries, ignited a flurry of protests, litigations and uprisings into the early twentieth Century. By the time the New Reserves were abolished in 1922 and reinstated simply as State Forests, serious ecological, environmental and social damage had already been sustained. Ecologically, in addition to slopes that had been left bare, other areas that were replanted did not yield nearly the variety of products used by the locals as rendered by a naturally regenerated forest and as a result of heavy restrictions on grazing, use of the remaining pastures by nomadic Gadhi herders increased substantially leading to severe soil degradation and erosion in certain areas. Long-term inhabitants also sustained more direct social damage as a result of the Indian Forest Act of 1865. Consequently, the indigenous forest management systems and customary land rights of the native people were abolished. This not only greatly reduced the peoples' subsequent ability to manage their forests but also translated into a deterioration of forest quality.

2.2.4 Current Period (mid-20th century – Present)

India's independence in 1947 from Britain did not so much affect the manner in which resources are extracted or the importance of economic growth as simply changing who reaps the benefits; from the Queen of England to the government in Delhi. The economic development of previously remote villages has rapidly accelerated since the 1970s spurred by the near frantic pace of road and railway construction throughout much of the Himalaya by the Indian and Chinese military between 1950 and the mid-1980s. While the length of motorable roads in Kullu District has increased at an average annual rate of over 2% since 1971, the number of registered vehicles and the number of kilometers driven by each vehicle has risen much more dramatically; over 20% and 5% per year, respectively, since 1971. In many villages, the proposed plan for economic growth, which may include increased industrial capacity, expansion of commercial agriculture or more recently, horticulutre, extraction of forest products, development of hydroelectric capability, or increasing tourism potential, is simply imposed on an area by governments or developers situated far away from the affected region. Until very recently, in most instances local leaders and villagers were excluded from discussions regarding territorial and land use policies which would have direct impact their livelihoods but which were more often than not meant to benefit the local elite or government representative rather than the community. The main problem then seems to be a conflict between the subsistence-level needs of many of the mountain communities and the commercial-level output demanded by national and global growth standards. The Kullu Valley serves as an example and case study of this type of problem in the Himalaya.

2.2.5 Cultural Summary

There emerge four distinct periods in the history of the Kullu District with respect to population change. The first period, beginning with the initial settlement of the Kullu Valley several millennia ago up to the turn of the 20th century, saw a gradual, fluctuating increase in the number of people inhabiting this mountainous region with the first official Census of India recording a population of 119,000 in 1901. Over the next 60 years, the population increased to about 160,000 and by 1971 in a span of only 10 years, it jumped to 200,000. Between 1971 and 2001, the Kullu District experienced an average population growth of over 20% per decade to reach the current 400,000 permanent inhabitants. This population growth and the associated intensification of infrastructure initiated in the late 1970s can be attributed to two main factors; the conflict in Kashmir and the shift from subsistence agriculture to a cash-crop economy based on fruit growing (Gardner, 2001 *pers comm.*). The former factor effectively closed the Kashmir region to tourism, diverting most of the local tourists to Himachal Pradesh beginning in the mid-1980s. India's tourism industry relied heavily on domestic and foreign visitation to Kashmir so in order to minimize economic losses the local and federal governments began to heavily promote Himachal Pradesh and the Kullu Valley in particular beginning in the early 1980s as an equally appealing tourist destination with the added bonus of being closer and thus more accessible to local travelers coming from the plains. As a result of these promotional efforts, visitation to the Kullu Valley grew dramatically from about 18,500 tourists in 1971 (Singh, 1989), to 290,000 in 1991, to the current estimate of 500,000 in 2001; an increase of 2,700% over a 30 year period with most (80%) of the tourists visiting between the months of April to June and September to October (Singh, 1989). The rate of development of tourist facilities including hotels, restaurants, roads, and attractions has more than doubled since 1980, especially along the transportation corridors between Manali and Kullu town and on marginal slopes. The consequent demand for seasonal labour, both in the service and construction sectors, has been satisfied by a large influx of migratory workers from the Kullu District as well as more distant regions including Ladakh, Tibet and Nepal. Population density has more than doubled between 1961 and 2001 from less than 25 persons km^{-2} to 65 persons km^{-2}, significantly increasing the pressure on resources and the limited area available for settlement.

The latter factor resulted in the conversion of abandoned and marginal agricultural land into relatively more stable (both physically and economically) orchards. Commercial orchardry was first proposed in the Kullu in the late 1800s by British settlers who recognized that fruits such as apples, mangos, and pears could easily be grown on the warm and moist alluvial fans in abundant quantities. The main factor which stalled this plan for another 70 years was the lack of processing facilities close to the orchards since the fruit would rot in transport before reaching the processing centres on the plains. With the construction of motorable roads connecting the Kullu Valley with Chandighar and Delhi to the south beginning in the 1950's, transport times became acceptably shorter. Also the redistribution of lands adjacent to traditional settlements from the government to local villagers under the nautor land scheme of the 1950's opened previously inaccessible areas to agriculture, horticulture and development (Gardner, 2001 *pers comm.*). The flourishing fruit industry in Himachal Pradesh and Kullu Valley in particular has attracted a significant number of immigrants from neighbouring regions and states who have permanently or temporarily settled here in an attempt to profit from the horticulture business. In combination, both of these factors resulted in a significant increase in the permanent and seasonal population of the Valley as well as in the risk of exposure of people and infrastructure to naturally occurring denudation processes.

2.2.6 Land Management and Land Use/Cover

The original inhabitants of the Himalaya minimized risk and their exposure to the intense physical processes of erosion operating in this rugged and ever-changing mountain environment by paying close attention to the terrain and understanding the dynamic nature of the surrounding landscape. Their small numbers, subsistence lifestyle, reliance on access to good grazing areas for their animals and virtually no means of controlling floods or mass wasting phenomena meant that places of permanent settlement, agricultural fields as well as transportation networks had to be carefully planned in order to avert disaster. In other words, living and surviving in the Himalaya 2,000 years ago required intimate knowledge of principles related to geomorphology, geography, engineering and hydrology in order to effectively avoid areas prone to landslides, debris flows, floods, rock fall and bank erosion. Of course with only a few hundred or thousand people in the entire Kullu Valley, there was no lack of safe sites to chose from, no external pressures or influences dictating where they should open an agricultural field and no one demanding they extract more resources than were necessary for their subsistence. In essence, these early dwellers relied on their indigenous knowledge of the landscape gained over decades of experience to avoid areas affected by processes of physical erosion inherent to all mountainous regions.

Beginning with the centralization of government by the Gorkhas in the 1600s, the power to make decisions regarding land use, resource extraction, development and settlement patterns has been steadily shifting away from the local inhabitants of the Himalayan valleys to political leaders and corporate managers who are in many cases completely disconnected from the areas which bear the consequences of their decisions. Perhaps even more alarming are the differences in the reasons for these decisions between the local and remote stakeholders. For the local people the consequences of their land use management decisions quite literally impact their very livelihoods and thus their reasons are more intimately tied to trying to maintain a balance between their needs and the capacity of the land. As has already been demonstrated above, the decisions made by those more detached from the affected areas are more for reasons of power, wealth and status, perhaps not solely their own but the regions or countries as well.

Although the level of resource extraction (i.e. mining and clear cutting) and the consequent land degradation varies considerably from one Himalayan valley to another due to differences in management policies, available resources and a host of other factors, what is certain is that the effects of population and land use/cover change are as varied as the landscape itself and must be considered on a very localized basis (Schweik *et al.*, 1997). It must be understood that the Himalaya in general has not been completely deforested, and not all of the rivers have been dammed and minerals extracted. Although this seems like an obvious statement, it is exactly this type of perception that advocates of the Theory of Himalayan Degradation have been promoting over the past several decades (Ives and Messerli, 1989). Unfortunately, since the mid-1750s there have been numerous valleys which have, at one time or another, been completely deforested, and certainly more are moving along this path. In these specific cases, clear cutting has caused massive slope erosion and removal of topsoil resulting in loss of lives, land productivity and carrying capacity leading to an uninhabitable wasteland. However, in many other valleys the forest cover has been stable for centuries, population pressures have remained relatively low and land use management practices are geared towards long-term sustainability and ecological balance. Still in other areas, such as the Indo-Gangetic plains south of the mountains including the Kullu Valley, inhabitants are being exposed to an increasingly greater level of risk from natural erosion and denudation processes such as floods, landslides, and rockfall. In these particular areas, the problem is not necessarily deforestation or degradation of the mountain slopes but rather the settlement patterns of the increasing number of immigrants (Sidle *et al.*, 1985). In the case of some Himalayan valleys, the problem stems from the fact that the limited land deemed suitable for habitation (i.e. flat and well drained) tends to coincide with areas prone to mass wasting activity, flooding and bank erosion. In the plains, settlements are often located along rivers which provide easy access to resources including water for food, bathing, and transportation. In these areas, land use management decisions may not have led directly to the destabilization of slopes or more frequent flooding but have instead attracted or forced a large number of people to settle in a potentially hazardous area. Even when the immigrants are relatively wealthy and can afford to purchase land, which is rarely the case, often there are few areas available that are not subject to erosion, inundation and/or deposition processes. In many cases, the immigrants, who are often poor, settle in marginal areas such as adjacent to the floodplain or on fragile slopes which, through indigenous knowledge and an appreciation of the dynamic nature of the landscape, the local inhabitants have avoided.

Chapter 3 Methods

3.0 Introduction

The main hypothesis being tested is that the susceptibility of people and property located along the main transportation corridors in the Kullu Valley to processes of erosion and denudation has increased between 1972, 1980 and 1999. More specifically, the aim is to assess how changes in land use/cover, specific terrain variables, climate, and earthquake frequency and magnitude have influenced the exposure of people and infrastructure to mass wasting and denudation activity (see Section 1.1). The following data were used in hypothesis testing; locations of erosion and denudation processes along the main highways and roads in the Valley; terrain variables associated with those processes; land use/cover for 1972, 1980 and 1999; a climate record (including precipitation and temperature) for the past century; and a record of earthquake activity between 1882 and 2004. The hypothesis was tested by first analyzing how the input data have changed over time and secondly by determining the impacts of these changes on the susceptibility of people and infrastructure to erosion and denudation processes. A comprehensive GIS database containing all of the pertinent and available factors affecting slope stability and denudation was compiled and can be applied to the modeling of future changes in susceptibiliy and to the distribution of hazard sites.

Discussion of the methods begins with a description of the steps taken to generate a digital elevation model (DEM) of the study area in Section 3.1. Techniques used to geo-correct the input maps using ground control points (GCPs) and to generate and assess the quality of the slope gradient and aspect layers are presented. The creation of a road map of the study area using global positioning system (GPS) data constitutes Section 3.2. Processing of the Landsat data acquired in 1972, 1980, and 1999, its radiometric calibration and the elimination of cloud-covered areas prior to classification is discussed in Section 3.3. Classification of the Landsat data which served as the basis for generating land use/cover maps of the study area for the three time periods mentioned above is presented in Section 3.4. Section 3.5 describes the generation of a land use/cover map for the period around 1920 based on historical terrestrial photographs. The creation of an inventory map of all known and potential sites of mass wasting and denudation activity is discussed in Section 3.6. Techniques used in the collection of variables for each site and the modeling of deposition and inundation zones for landslides, debris flows, rockfall, and floods, and bank erosion areas are included in subsection 3.6.1. Land use/cover change analysis is the topic of Section 3.7. The aim of Section 3.7 is to elaborate on the spatial changes of each land use/cover type between 1972, 1980 and 1999 and to uncover the main trends in land use/cover change using pair-wise comparisons. A discussion of the effects of climatic and seismic factors on the state of natural hazards in the Kullu Valley is presented in Section 3.8.

Government of India security restrictions prevented access to several critical data sources including large-scale topographic and geological maps as well as climate data, specifically temperature records. These restrictions directly affected data analysis procedures and interpretation of results as will be discussed further.

3.1 DEM Generation

Digital elevation models often constitute the basic analytical layer in GIS-based slope stability analysis (e.g. Iwahashi *et al.*, 2001). Several important variables used to assess slope stability, including local relief, slope aspect and slope gradient can be determined from a DEM or its derivatives (Saha *et al.*, 2002). Three Russian digital (scanned) topographic maps pusblished in 1982 served as the basis for a digital elevation model of the study area located at 692,000 mE – 713,960 mE to 3,528,895 mN – 3,587,995 mN UTM 43N (see Figure 2.2). The 1:100,000 scale maps with 40 m contour intervals were cropped and edge-matched to show the area of interest on a single layer. This layer was imported into ArcView© to check projection alignment against a panchromatic ETM7+ image and 40 ground control points acquired in the field using global positioning system (GPS). The ETM7+ image, with a pixel resolution of 15 m was compared with the topographic map to verify proper alignment of the main physical features including mountain ridges, rivers, streams and roads between both data sets. As an additional check, 40 ground control points (GCPs) were overlaid onto the topographic map to verify the correct location of a number of key intersections and other cultural features. The GCPs were acquired mainly at road intersections and on bridges using a GPS unit attached to a laptop computer running ArcView and Tracker Analyst© software. Tracker Analyst logged position data from the GPS through a serial link at a rate of 1 point every 2 seconds for at least 15 minutes at every control point thus each GCP consists of a minimum of 250 position fixes. Deckert and Bolstad (1996) found that in mountainous terrain at least 200 positions should be collected at each location in order to minimize positional error.

An estimate of the mean horizontal and vertical error was computed using the variation in Easting, Northing, and elevation for each GCP. The quality of each GCP was assessed based on the horizontal dilution of position (HDOP) and the number of satellites used to acquire each point. Poor quality positions (i.e. those with fewer than 4 satellites and an HDOP value of less than 4) were eliminated (B.C. Ministry of Forests, 2001). The horizontal root mean square error (RMSE), a common measure of agreement, between the topographic map and ETM7+ scene and topographic map and GCPs was deemed accptable at <15 m (less than one pixel) and <5 m, respectively.

The topographic map served as a raster template from which all contours between the elevations of 1,025 and 5,120 m were manually on-screen digitized into a vector data structure as polyline features in ArcView software. These contours were used to create a triangulated irregular network (TIN) which was then interpolated into a digital elevation model (DEM) with 30 m pixel resolution to match the resolution of the ETM7+ data. Excess angularity resulting from the interpolation algorithm was filtered out by convolving a 3x3 median window over the DEM. A statistical comparison using a paired t-test between the DEM and 66 elevation and slope gradient points measured with an altimeter and inclinometer, respectively, produced good overall agreement (t-stat = 0.29, t_{crit} = 2.00, p-value = 0.78 at the 95% confidence interval) (Coops, 2000; Mantovani *et al.*, 1996). With the vertical accuracy of the DEM verified, slope gradient and slope aspect layers were generated using the Spatial Analyst extension. Both images were smoothed using a 3x3 median filter and converted to Idrisi 32-compatible format to facilitate subsequent conversions between ArcView and Idrisi software as neither package satisfactorily handled all of the required analyses.

3.2 Road Map Generation

Unavailability due to Government of India security restrictions of a reliable general reference map of sufficient scale (i.e. $\leq$ 1:25,000) for hazards mapping necessitated the creation of a road map for the study area. The GPS/laptop/Tracker Analyst system provided a means of acquiring frequent location data while traveling along the roads on a motorcycle. The resulting database of locations was filtered to eliminate poor quality positions and the remaining positions were used to generate a vector point file of roads in the study area. General road alignment was checked by overlaying the point file onto the ETM7+ panchromatic scene. Although some of the smaller roads could not be resolved on the panchromatic scene, it nevertheless proved useful as a means of visually assessing the accuracy of the vector point file. A roads layer was created by extending vectors between the points and converting the vector file into a raster image.

3.3 LandSat Data Processing

The land use/cover maps were generated using the following data sources; Landsat satellite images from 1972, 1980, and 1999, a 1999 land use/cover map for a portion of the valley, ground validation polygons acquired in 1999 and 2000, DEM, slope, and aspect layers, Indian national census data, and informal interviews with long-term residents. Data and methods used to create the historical land use/cover map are discussed in Sections 3.4 and 3.5.

Landsat 1 (1972) and 3 (1980) data consisted of 4 multi-spectral scanner (MSS) bands (blue, green, red, and near-infrared) while Landsat 7 (1999) data comprised of 7 thematic mapper (ETM7+) bands (green, blue, red, near-infrared, mid-infrared, thermal, and far-infrared) plus a panchromatic scene. The thermal bands (ETM7+ 6-low and 6-high) were not used in the analysis as they did not sufficiently discriminate between features of interest as well as the other bands. In order to minimize processing time, each image was cropped to show only the study area (692,000 mE – 713,960 mE, 3,528,895 mN – 3,587,995 mN UTM 43N) (see Figure 2.2).

As a preliminary step, all areas affected by clouds and cloud shadows were eliminated from the scenes and subsequent analyses. More than 15% of the ETM7+ scene was affected by clouds and cloud shadows. Although several automatic procedures are available for detecting and eliminating cloud-affected pixels (e.g. Sanchez, 1992), a simple supervised classification was used to differentiate cloud and non-cloud pixels using all available bands for the ETM7+ scenes (Fleming, 1988). A training image was created by on-screen digitizing 40 cloud and non-cloud polygons on a false color ETM7+ composite (bands 4, 3 and 2) which provides excellent cloud/non-cloud, and snow/ice discrimination (Lillesand and Kiefer, 1995). Quality of the resulting mask was assessed by overlaying it onto each of the ETM7+ bands and comparing the number of non-cloud pixels to cloud pixels based on the spectral value derived from training histograms. On average, less than 0.1% of all pixels were wrongly classified as cloud, so the cloud mask was applied to all ETM7+ and MSS 1 & 3 input bands.

Radiometric calibration, a procedure, which addresses the issue of sensor degradation over time by converting raw digital values into calibrated radiances, was performed in the Idrisi program on the MSS scenes using built-in gain and offset parameters (Thome *et al.*, 1997). The ETM7+ scene was calibrated using parameters found in its metadata file. Using the appropriate band number and date of scene acquisition (obtained from the respective metadata file), each band was calibrated individually. The scenes also were corrected for atmospheric path radiance by the dark-object correction method using subtraction and a linear stretch (Chavez and Bowell, 1988). Dark-object correction first requires the identification of a naturally dark object (e.g. a deep, clear water body) which can be accomplished by reclassifying each band in each scene using a spectral threshold value above which all other areas are discarded. The remaining areas are then inspected to find the lowest digital value in each band in an area common to all images. Following subtraction of the lowest detected value in all bands from each input band, all scenes are linearly stretched to an 8-bit scale. These procedures are crucial in change detection over time because they minimize differences in the spectral responses in images taken on different dates or from different Landsat platforms so that the images can be compared directly (Ulbricht and Heckendorff, 1998; Lillesand and Kiefer, 1995).

The satellite scenes were already projected to UTM-43N using WGS84 ellipsoid and required no further geometric rectification. The 30 m spatial resolution of the ETM+ scene was adjusted to conform to the base resolution of 57 m following classification in order to minimize geometric resampling errors.

3.4 LandSat Scene Classification

Classified satellite imagery is often used to map the spatial distribution of landslide controlling factors such as land use/cover (Larsson, 2002; Zhou *et al.*, 2002; Mantovani *et al.*, 1996). Application of the maximum likelihood supervised classifier to the classification of satellite imagery is well established in the literature (Saha *et al.*, 2002; Elumnoh and Shrestha, 2000; Lilesand and Kiefer, 1995; Wilson and Franklin, 1992; Gong and Howarth, 1990). A supervised classifier requires prior knowledge of the types of land uses/covers found in an area and, in instances where the relative distribution of land use/cover types is known, the information can be incorporated as *a priori* knowledge into the algorithm. The current distribution of land use/cover types was available from a 1999 land use/cover map for a portion of the study area and ground validation surveys carried out in 1999 and 2000.

The partial land use/cover map acquired from the Science and Technology office, Kasumpti, India, shows 9 unique land use/cover categories which were subsequently merged into 4 classes as described below. The map was first scanned at 600 dpi into 12 sections which were subsequently spliced together into a single raster layer. Since the original projection was unknown, it was geo-registered in Idrisi to a UTM-43N projection and coordinate system using a first order polynomial function with the same 40 GCPs as described previously. A root-mean squared (RMS) error of 6 m was deemed acceptable (well within the original 30 m pixel resolution). The geo-registered map was imported into ArcView to serve as a raster template from which the land use/cover polygons were on-screen digitized as vector polygons. The completed map and associated database were then converted to a raster grid data structure and imported into Idrisi for use as a training image.

Training images contain polygons identifying areas of known and ideally homogeneous land use/cover type and provide the spectral statistics used in classification procedures to assign the remaining unclassified pixels to a land use/cover type. A secondary land use/cover ground validation layer was generated from several field surveys as well as from discussions and informal interviews with local inhabitants throughout the study area in 1999 and 2000. Four primary land use/cover categories were identified as described in detail in Section 2.1.4: Agriculture, Clearing, Forest and Settlement.

Two additional layers showing hydrology and transportation, were derived from the topographic and road maps and ETM7+ scene. The hydrology layer was created by first digitizing the Beas River from the partial land use/cover map and panchromatic ETM7+ scene as a polygon and then adding all other rivers and streams as vector lines from the topographic map. According to available maps and literature, the road network in the study area was non-existent in the 1920's except for cart tracks and trails (Gardner, *pers comm.*, 2001). It was upgraded to its current status in the late 1970's (Singh, 1989; Gardner, 1997). A separate transportation layer for 1920 and 1972 was created by editing the most current transportation layer to reflect the absence of particular roads which did not exist in those time periods. The transportation layers were merged with the Settlement category in each land use/cover map and hydrology was used as a mask to eliminate streams, rivers and other water bodies which were not considered in the land use/cover change analysis.

One of the main problems with using only spectral data to generate a classified land use/cover map for mountainous terrain is the topographic shadow effect caused by sun azimuth and elevation and relief (Colby, 1991; Civco, 1989). Spectral reflectance of a given land use/cover type is reduced and modified in shadows compared with the same land use/cover type in a sunlit area, which may lead to serious misclassification errors (Taherkia and Collins, 1986; Holben and Justice, 1981). According to Elumnoh and Shrestha (2000), Frank (1988), and Lee and Stucky (1988), classification accuracy in mountainous terrain can be improved by using band ratios and vegetation indices in conjunction with topographic information derived from DEM, slope, and aspect images (Franklin and Peddle, 1989). In addition to 4 MSS bands (4, 5, 6, and 7) and 6 ETM7+ bands (1-5 and 7), DEM, slope and aspect images were used to generate the following transformations:

Normalized difference with near-infrared and red bands

NDVI1 = (TM4 – TM3) / (TM4 + TM3)

NDVI2 = (MSS7 – MSS6) / (MSS7 + MSS6)

Vegetation Index Ratio of near-infrared and mid-infrared bands

VI2 = (TM4/TM5) x (S.D. TM4 + S.D. TM5)

Reflectance/absorptance ratio

R/A = TM4 / (TM3 + TM5) x (S.D. TM4 + ((S.D. TM3 + S. D. TM5) / 2))

Band ratio

BR = TM7 / TM5

where TM 3-5 refers to bands 3 through 5 for the ETM7+ sensor, MSS 6 & 7 refers to bands 6 and 7 for the MSS 1 & 3 sensors, and S.D. is standard deviation (after Elumnoh and Shrestha, 2000).

Vegetation indices are widely used to discriminate between vegetated and non-vegetated areas based on the relative absorption of incident radiation by organic and inorganic land uses/covers. Even in areas of topographic shadows, these transformations proved useful in distinguishing between Agriculture and Forested areas from Settlement and Clearing cover types. Reflectance/absorptance ratios reduce the effects of topographic shadows by equalizing the differences in reflectance based on a ratio between band 4 and a combination of bands 3 and 5. Topographic shadows in band 4 (near-infrared) are often not as pronounced as in band 3 (Red) and much more pronounced than in band 5 (mid-infrared). Thus by employing the standard deviation of bands 3 and 5 in the computation of the ratio, an average, equalized, reflectance is computed.

It was not possible, nor efficient, to use all available bands, transformations, and topographic indices in a maximum likelihood classifier primarily because Idrisi allows only 7 input bands but also because much of the information in the different bands is redundant, making subsequent interpretation cumbersome and time consuming. Several preliminary classifications were carried out using the ETM7+ dataset in order to determine the utility of each input layer to clearly distinguish between each of the 4 land use/cover types. Means, standard deviations, and principle components analysis (PCA) results were used to eliminate redundant data sources. Bands 1, 2, 4, and 7 along with

NDV1 and BR, generated superior results with overall classification accuracies of 85.8%, and a Kappa (k) statistic of 0.78. The k statistic, an effective estimator of classification accuracy, accounts for the possibility that a random classification could produce agreements (Brown *et al.*, 2000). In this case, the classification results are 78.0% better than those generated randomly.

In an attempt to improve accuracy, the percent cover of each land use/cover type was calculated from the training image (which shows complete land cover for ~4% of the study area up to 300 m above the valley floor) and 1991 Census of India data. The percentage for each land use/cover category shown in Table 3.1 represents the probability of that land use/cover occurring based on its current known distribution relative to the other 3 classes. Overall classification accuracy can be improved by incorporating prior probabilities (Pedroni, 2003; Lillesand and Kiefer, 1995). Inclusion of *a priori* probabilities in this case improved the classification slightly, resulting in an overall accuracy of 86.7% and a k statistic of 0.80.

Table 3.1 Percent cover for each land cover type for 1999 partial land cover map.

Land Cover/Use	% of Total Area
Agriculture	26.3
Clearing	21.2
Forest	44.9
Settlement	7.6

Classification of the 1999 dataset was initiated by generating spectral reflectance histograms for each land use/cover type and input band. Rarely are histograms for each cover type and input band normally distributed about a well-defined mean with low standard deviation and minimal overlap between different land uses/covers. Thus, each histogram was checked for evidence of multimodality or outliers and the minimum and maximum values were adjusted in order to more precisely define the spectral response of each land use/cover type for each band. This was accomplished by manually querying and adjusting the spectral values in all input bands for each land use/cover type to maximize class homogeneity. Output from the maximum likelihood operation was compared with the training image in an error matrix to assess individual and overall classification accuracy (Table 3.2).

Table 3.2 Summary error matrix results for 1999 partial land use/cover map and 1999 classified land use/cover map.

Land cover class	**Producer's accuracy**	**User's accuracy**
Agriculture	70.0	80.0
Clearing	95.0	82.0
Forest	96.0	95.0
Settlement	62.0	61.0
Overall accuracy = 86.7% Kappa statistic = 0.80	Total pixels used = 13,110	

Omission and co-mission errors of Settlement areas as Agriculture represent the largest misclassification problem. Significant overlap of reflectance values for these land use/cover types in the input layers, particularly band 4, is the most probable reason. This overlap likely is due to high spectral heterogeneity in the training classes resulting from a mix of land use/cover types in the training areas. There also is some confusion between the Clearing and Agriculture categories, most likely due to the time of year the scenes were acquired (mid-fall), when some partially harvested fields may resemble sparsely vegetated clearings. According to available literature, classification accuracies of 65% and above are generally regarded as acceptable in mountain environments (Franklin and Wilson, 1992) thus an accuracy of 86.7% was considered sufficient to warrant further analysis. It must be noted that this accuracy only reflects the accuracy of the classification within the training image area and not the whole study area. The results of this classification are shown in Figure 3.1a.

Classification of the 1972 and 1980 Landsat scenes proceeded in a similar fashion despite the lack of unique training images for those specific dates and the results are shown in Figures 3.1c and 3.1b, respectively. To address this issue, the 1972 and 1980 signature files were generated using an adjusted 1999 training image with MSS bands 1 through 4, and NDVI2 as input. Although the wavelengths for MSS bands 4 – 7 correspond directly with ETM7+ bands 1 – 4, the spectral signatures for each land use/cover type derived from the 1999 data could not be used directly because of different sun elevation and azimuth angles between the 3 scenes. The 1999 training image was edited based on information provided by several long-term local residents who identified a number of areas where land use/cover had not changed over the past three decades (Virgo and Subba, 1994). This information, recorded on ground-based photographs, was used to adjust the ground validation polygons in the 1999 training image and produce training images for 1972 and 1980. Percent land use/cover values obtained from the Town and Country Planning Department of Himachal Pradesh, for 1972 and 1987 provided *a priori* input into the classifier for the 1972 and 1980 datasets, respectively.

Following the classification procedure, the signature files were edited to maximize homogeneity within classes and minimize overlap between classes. Final classification accuracy was checked against the respective training images using an error matrix and *k* statistic, which indicated an agreement of 0.75 and 0.71 for 1972 and 1980, respectively. Overall accuracies of 84.0% and 82.0% for the 1972 and 1980 land cover maps, respectively, were deemed adequate.

To facilitate subsequent overlay analysis, the 1999 map was spatially resampled using a nearest neighbour algorithm which reduced the original 30 m pixel resolution to 57 m. All three land use/cover maps were smoothed using a low-pass median 3x3 filter in order to improve homogeneity of the land use/cover classes and remove classification noise (Holmes *et al.*, 2000; Lamb *et al.*, 1987).

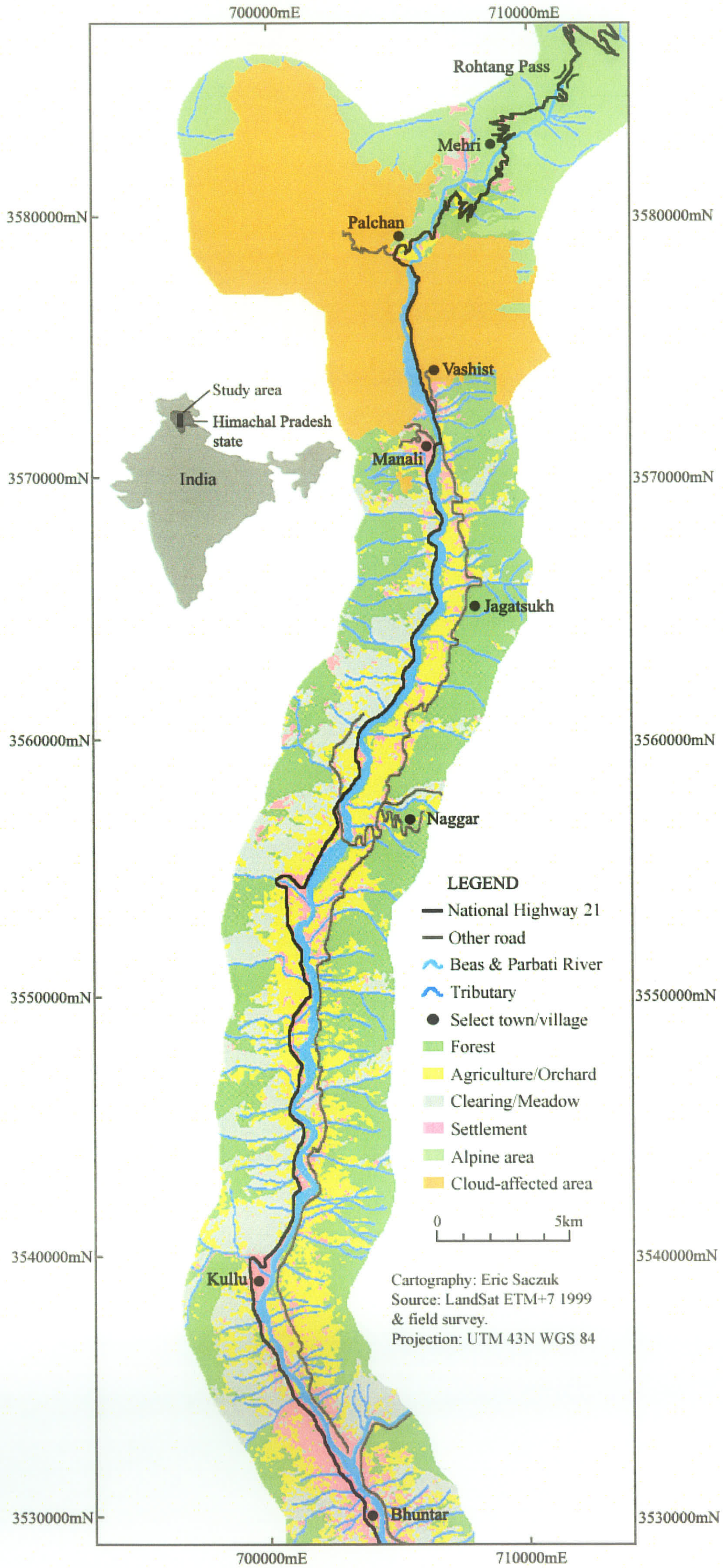


Figure 3.1a 1999 land use/cover map for the study area in Kullu Valley. Classification area extends upto 3 km on either side of the Beas and Beas Kund River, which corresponds to the natural break-in-slope. (Author)

Figure 3.1b 1980 land use/cover map for the study area in Kullu Valley. Classification area extends upto 3 km on either side of the Beas and Beas Kund River, which corresponds to the natural break-in-slope. (Author)

Figure 3.1c 1972 land use/cover map for the study area in Kullu Valley. Classification area extends upto 3 km on either side of the Beas and Beas Kund River, which corresponds to the natural break-in-slope. (Author)

3.5 Historical Land Use/Cover Map

The techniques and data sources used to generate the historical land use/cover map for the period around 1920 differed significantly from those used to create the three maps described above. The main sources of information used for this map were; historical black and white photographs, current photographs taken from the same locations, GPS positions of those locations, a DEM, local knowledge of land use/cover change, 1999 training image, and results of a 3-dimensional viewshed analysis. Data acquisition, processing, and synthesis techniques are discussed below.

15 large-format black and white photographs, taken between 1900 and 1930 by British Army personnel, local residents, visitors, and Survey of India staff, provided evidence of the location and distribution of various types of land use/cover for that time period. Copies of the photos were acquired from the British Library, Royal Geographical Society and private collections (Figure 3.2). After a brief initial examination, it was decided that the 4 land use/cover categories of Agriculture, Clearing, Forest, and Settlement could be consistently identified in the historical photographs. A comprehensive and accurate interpretation of the photographs required input from local inhabitants and long-term residents. Thus, the historical photographs were shown to several long-term residents and, during informal interviews, they were asked to classify the photos into each of the four land use/cover categories. The interpreted pictures were then compared and an aggregate land use/cover image was produced for each historical photograph. In most cases, the interpretations among residents corresponded closely. In

a few cases, manual photo interpretation techniques were applied in order to resolve conflicts.

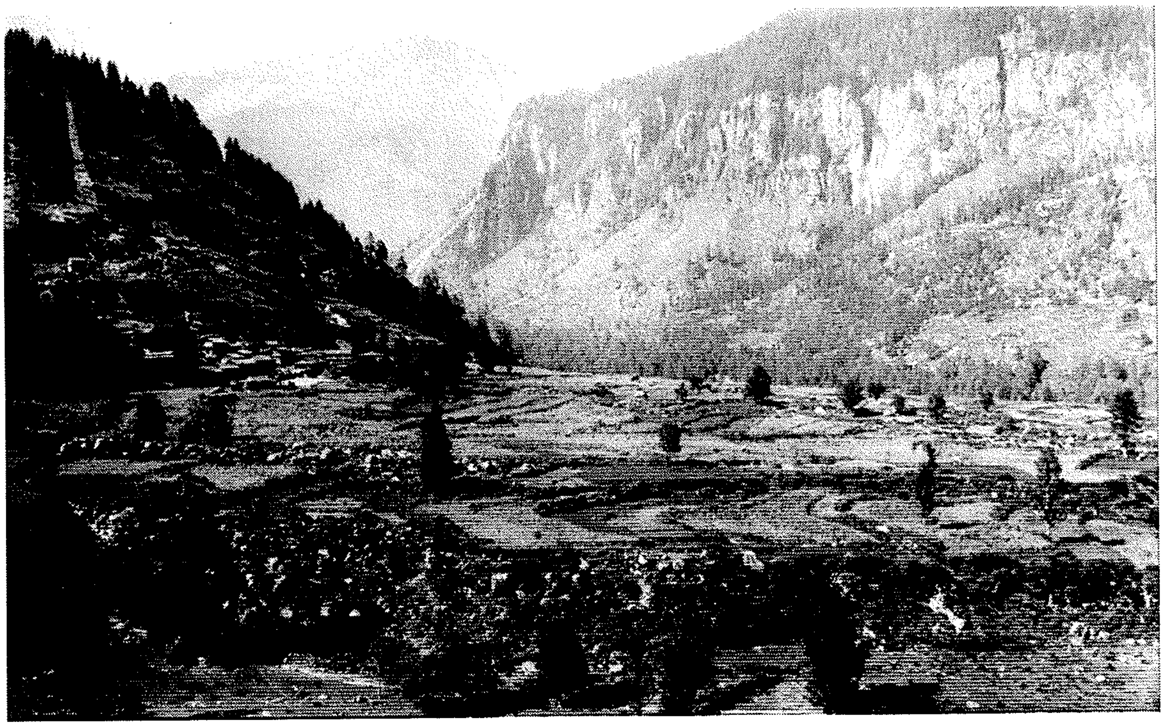


Figure 3.2 View of Manali circa 1904 looking north. (Stotherd Collection)

Some of the historical photographs included a brief description of the scene, which helped to identify the location from which they were taken; most, however, did not. During several field reconnaissance sessions, the locations from which the pictures were taken were found with the help of residents. At each location of the old photos, a new photograph was taken with either a digital or 35 mm camera, the position recorded with a GPS, and the general viewing direction determined with a compass. The analogue photographs were scanned and digitally spliced (where necessary) into a single picture. Following this, the picture locations determined using GPS, were plotted onto the DEM in order to carryout viewshed analysis in ArcView software. Viewshed analysis identifies visible and non-visible areas from a set of vantage points (i.e. photograph locations) based on topography (i.e. DEM) in all directions (Wang *et al.*, 2000). Boolean viewshed masks were generated for each photograph location separately then edited to mask out areas not visible from the location based on viewing direction and camera lens field-of-view parameters. A composite viewshed mask was generated by combining the individual masks using a logical OR function in Idrisi after the files were exported from ArcView as raster grids. The mask was then imported back into ArcView and applied to the 1999 partial land use/cover map to eliminate all areas not visible from the historical photo locations. The aim of this was to use the partial land use/cover map as the starting point for the generation of a historical land use/cover map by successively editing current (i.e. 1999) land use/cover polygons to reflect the land use/cover type shown in the historical photographs. To facilitate this, a 3-dimensional perspective view was generated for each photo location using GPS locations, the DEM, compass viewing direction, and the masked partial land use/cover map as input (Figure 3.3) (Fisher, 1992).

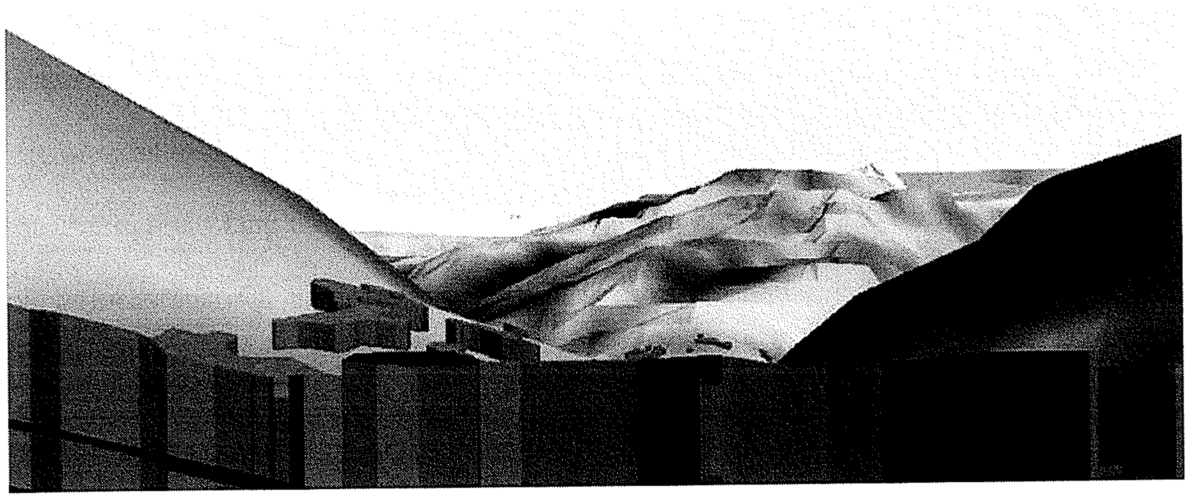


Figure 3.3 3-D view showing TIN and extruded buildings. (Author)

The 3-dimensional perspective facilitated editing of the 1999 land use/cover polygons to match those shown on the aggregate land use/cover photographs, as defined by local residents. Thus, the output map shows 4 land use/cover categories for all areas visible in the historical photographs for the period 1900 - 1930 (Figure 3.4). Although the accuracy of this map could not be quantified, the percent distribution of each land use/cover category on the map corresponded well with the distributions for similar land use/cover categories published in the 1921 Census of India.

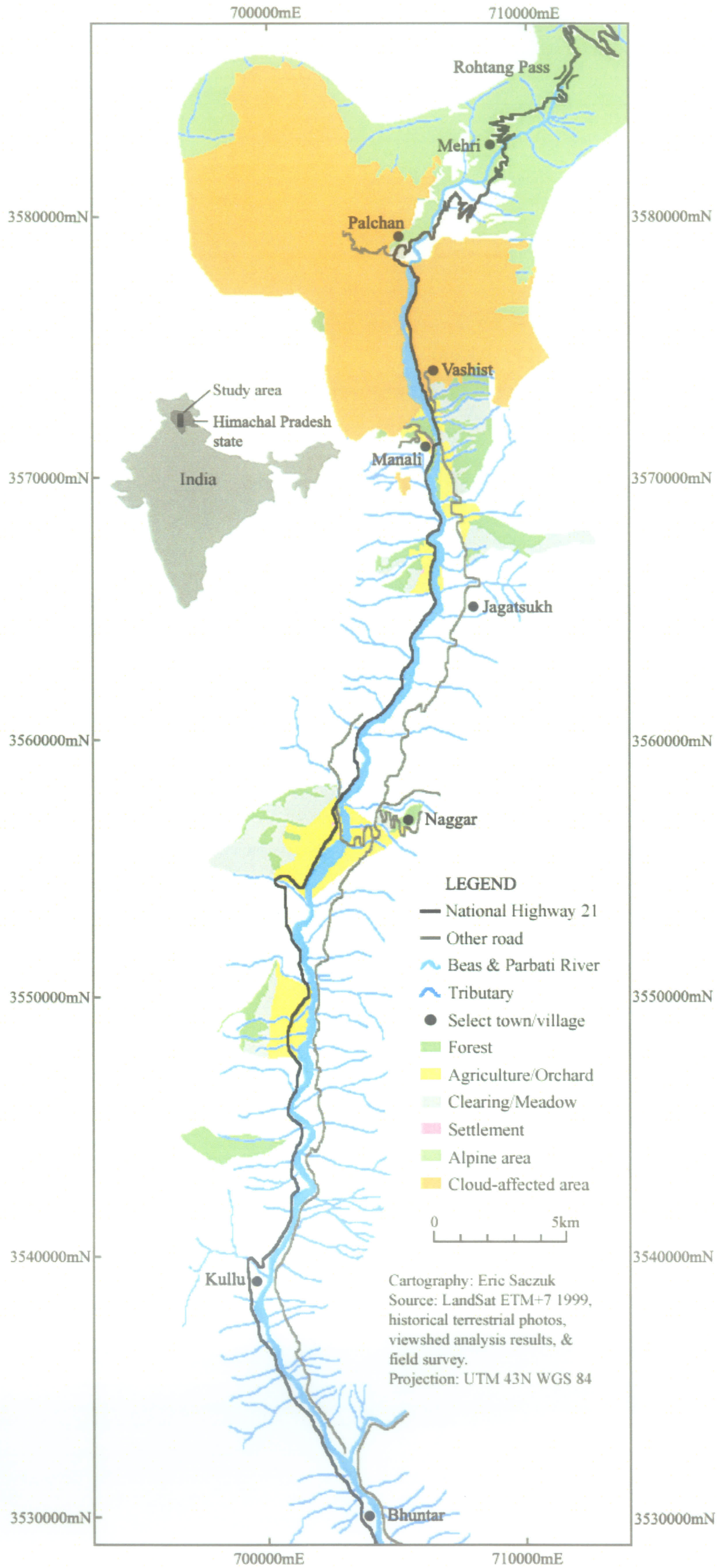


Figure 3.4 1920 land use/cover map for the study area in Kullu Valley. Extents of classification area determined by viewshed analysis based on areas visible on historical photos. (Author)

3.6 - Susceptibility Mapping

Landscapes dominated by chronic denudation activity, such as the Kullu Valley, are subject to a wide range of erosional processes. Most of the transport of surficial material occurs as small landslides, slumps, composite and progressive failures, debris flows, and rock falls (Dal and Lee, 2002; Gardner, 2002; Shroder, 1998). The lack of an inventory map of known and potential sites of slope hazard prompted two surveys (in 1999 and 2000), of landslide, debris flow, and bank erosion sites along all main roads in the study area. Both field surveys were carried out during the summer monsoon (July to August) to maximize the likelihood of directly observing these events as they are most frequently triggered by intense and prolonged rain events in this region. Frequencies and thresholds of triggering mechanisms such as rain storms or earthquakes which increase the probability of slope failure and flood occurrence could not be established because adequate records of specific events were not available.

The term hazard site, as used in the context of this study, defines an area which may be prone to any of the erosion or denduation phenomena mentioned previously over the span of several years. Inventory maps are of limited use according to Brabb (1984) as they represent only interpretations of a single researcher for a particular point in time and are thus subjective and too time-specific (Rowbotham and Dudycha 1998). This conclusion overlooks the obvious fact that factual information is normally part of any inventory, and that must preceed any subsequent hazard analysis or mitigation projects (Mantovani *et al.*, 1996; van Westen, 1994; Carrara, 1988). The ability of a researcher to consistently identify sites of mass wasting activity, slope failure and deposition, bank erosion, flooding, and other processes of denudation, is undoubtedly directly related to experience and the nature of the area being studied (van Westen, 1993; Carrara *et al.*, 1991). For this project, several researchers were engaged in the identification of potential hazard sites based on a number of geomorphic criteria, thus diminishing the effects of individual levels of experience.

Through their location and distribution, the association of known slope failure sites with certain factors such as rock or soil type, elevation, slope, aspect, land use/cover, drainage density, proximity to streams, proximity to fault lines/lineaments, slope curvature, and surface roughness has been used to predict other sites with similar terrain characteristics (Saha, *et al.*, 2002; Rowbotham and Dudycha, 1998). The importance of each of the factors mentioned above varies considerably between different regions due to local environmental differences in rock and soil type, land use/cover, drainage pattern, and human activity as well as the availability of data (Dhakal *et al.*, 1999). It is also important to consider that the conditions and factors governing the current state of geomorphic dynamic equilibrium change with time as well as the time-frame of the study. Factors such as land use/cover, surface roughness or soil type become progressively less important and geology and tectonic activity become more important with an increase in the time-frame of the study.

For this research, the term *release area* refers to a landslide scar or portion of a rock face from which material is known to have originated following activity. It can also mean the potential area from which rock or unconsolidated material may originate in the future. *Deposition area* is the zone of transportation or deposition for material which originated in the release area of a landslide or rock fall or from the mouth of a debris flow channel. It also includes areas affected by flooding and bank erosion processes. Data collected at each site and the variables used to create the hazard inventory and susceptibility model for areas affected by slope failure and denudation processes are described below.

3.6.1 Factors

Factors considered to be the main determinants in slope stability analysis include geology, slope gradient, slope aspect, elevation, soil type, land use/cover, ground water and, proximity to a fault line (Sarkar *et al.*, 1995; Zimmermann *et al.*, 1986; Crozier, 1986; Varnes, 1978; Coates, 1977). In this case, data about geology and proximity to a fault line could not be obtained because a detailed geological map was not available due to Government of India security restrictions governing this militarily-sensitve area. All other variables were collected during a survey of each site along NH 21, the left bank road, and several other paved roads in the valley (Table 3.3).

Table 3.3 Variables collected at the intersection of each hazard site with a road or structure.

Variable	Landslide	Rock fall	Debris Flow
Site ID	x	x	x
Northing	x	x	x
Easting	x	x	x
Elevation	x	x	x
Activity	x	x	x
Angle	x	x	x
Aspect	x	x	x
Picture #	x	x	x
Soils	x		
Height	x	x	
Width	x	x	x
Structure		x	x
Boulder		x	x
Angularity		x	x
Vegetation	x		x
Land use	x	x	x
Water	x		x

Geographical locations (UTM coordinates) were recorded using GPS, elevation at the road was acquired using an altimeter, and slope/channel angle, aspect, and size (i.e. height/width/depth, where applicable) were measured using an inclinometer, compass, and laser range finder and measuring tape, respectively. Qualitative variables including activity, soil type, vegetation cover, and land use/cover also were recorded based on observations and geomorphological interpretations made at each site. "Activity" refers to any evidence suggesting recent failure, including water seeping out of the slope or fresh deposits of colluvium or boulders. Soil type was listed as either fine, coarse, gravelly, or bouldery. Vegetation was recorded as none for bare slopes, grassy, shrubs, trees, or any combination thereof and land use/cover was recorded either as Forest, Agriculture, Clearing, or Settlement.

In addition to data collected in the field, the following characteristics for sites of landslide and rock fall activity were extracted from GIS layers; slope gradient, aspect and shape, elevation, land use/cover, and proximity to streams and Rohtang Pass. For quantitative factors, the mean, range and standard deviation were computed and for qualitative factors the most frequently occurring or extensive type were extracted (where applicable) for each hazard type. These factors provide additional information about the terrain conditions associated with known release areas of landslide and rock fall hazard.

3.6.2 Landslides

In the context of this research, landslides describe the downslope movement of unconsolidated material, typically colluvium, soil, vegetation, rocks, and sometimes human-built structures, mainly under the influence of gravity although their motion may be aided by the presense of water, ice, or snow. Motion is initiated when the resisting forces normal to the plane of failure are exceeded by the driving forces parallel to the plane of failure (González-Díez *et al.*, 1999). Resisting forces are often diminished by an increase in pore-water pressure. Water that has infiltrated below the surface effectively increases the pressure between grains, leading to a decrease in friction due to less contact between particles. Driving forces can be increased by lateral ground acceleration from earthquake activity, the removal of supporting material at the toe of the slope or an increase in the weight of the overlying material due to heavy precipitation, construction or the transport and deposition of material from upslope.

Criteria used to identify landslides are well documented in the existing literature (e.g. Brardinoni *et al.*, 2003; Rowbotham and Dudycha, 1998; Carrara *et al.*, 1991, 1977; Deoja *et al.*, 1991; Crozier 1986, 1973). In this study, sixty-one landslide release sites were identified in the field on the basis of one or more of the following criteria: poorly sorted colluvium deposits on the road or near the base of moderate to steep slopes (~15° - 50°); presence of control structures such as retaining walls or gabion baskets; shrubs or trees tilted in a down slope direction (Figure 3.5); surface tension cracks perpendicular to the slope; and unvegetated, depressed, and/or exposed slopes. A distinction was made between landslide, composite failure, and progressive failure (Varnes, 1978), however the term landslide encompasses all three slope failure types here. Following site identification, the landslide-specific attributes listed in table 3.3 were recorded for the release area.

Figure 3.5 Tilted tree and damaged retaining wall as a result of progressive surficial failure along NH 21 south of Manali. (Author, June 1999)

The approximate dimensions of each release area as measured in the field and sketched on a map provided the basis for the landslide release area GIS layers (van Westen, 1994; Haigh *et al.*, 1993). GPS locations recorded at each site were overlaid onto a DEM and panchromatic ETM7+ scene and served as the starting points for on-screen digitizing of the release areas as vector polygons according to the field measurements and sketches. Following conversion of the vector map to a raster file structure, an anisotropic dispersion algorithm was employed to model deposition zones for each landslide site using Idrisi software. Previous studies on landslide run-out modeling rely on a combination of gravitational potential and distance variables extracted from DEM derivatives such as aspect and slope (Crosta *et al.*, 2003; Xu and Lathrop, 1995) and the method here follows these techniques closely. The main aim of the modeling procedure is to recreate as accurately as possible the shape and size of six actual deposition areas observed and surveyed in the field. The model is not capable of predicting deposition areas of future or past events, *per se*, unless they happen to coincide with events observed and measured during the field surveys. Although the recurrence interval of the observed events was difficult to determine precisely, according to local residents and staff at the snow and avalanche sciences establishment (SASE *pers comm.*, 2000) the landslides and deposition areas identified and surveyed in the field were considered to be of similar magnitude and areal extent to previous events.

In Idrisi software, the DISPERSE module used to perform anisotropic modeling required that the analyst define the starting points for dispersion, direction in which the dispersion forces/frictions are operating, the force/friction images defining the resistance associated with movement across a surface, maximum dispersion distance, and the degree of allowable spread (*k*) (Idrisi, 1987). Raster layers of release areas, direction of dispersion, and force and friction were prepared for each site and served as input into the anisotropic dispersion model as discussed in detail below. According to the model parameters, forces promoting dispersion must be expressed on a scale between 0 (maximum force) and 1 (minimum force) and frictions resisting dispersion must be expressed as positive integers defining the cost associated with moving across each grid cell. Friction layers were standardized to 1 (minimum friction) through 100 (maximum friction). Forces promoting slope movement in the release area were expressed using the equation

$$Force_i = -0.195Ln(\beta_i) + 0.878 \qquad (1)$$

where $Force_i$ is the force for grid cell i within the release area, -0.195 and 0.878 are constants to standardize the equation to values between 0 (strongest force) and 1 (weakest force), and β is slope gradient derived through an overlay operation in Idrisi and checked against field measurements made using a compass (R^2 = 0.93) at each site. A slope gradient of 90° represents the maximum force which declines at the rate according to the equation as gradient approaches 0.5°.

A raster layer of friction for each site, standardized to 1 (minimum friction) through 100 (maximum friction) was generated using the equation

$$Friction_i = \frac{(0.4(d_i) + 0.8) + 107e^{-0.0516(\beta_i)} + f\alpha_i}{3} \qquad (2)$$

where $Friction_i$ is the combined average friction for each grid cell (i) outside the release area and 0.4, 0.8, 107 and -0.0516 are constants to standardize the equation to 1 through 100. Combined friction is the average sum of downslope distance from the release area (d_i), slope gradient in degrees (β_i) and $f\alpha_i$ which is a function of aspect (α_i). $f\alpha_i$ ranges between 1 ($\alpha_i = \alpha_{mean} \pm$ s.d.) and 100 ($\alpha_i = \alpha_{mean} \pm 180°$) as a function of sine of α_i. Friction due to downslope distance measured from the release area (d), increases from a minimum at the release area (d = 0) to a maximum ($d = d_{max}$), where d_{max} represents landslide run-out lengths based on field measurements or derived from literature for similar environments (Marston *et al.*, 1998; Sah and Mazari, 1998; Shroder Jr., 1998).

Minimum surface friction (i.e. 1) occurred on slopes closest to the release area with maximum gradients and aspect equal to α_{mean}. Maximum friction (i.e. 100) occurred on slopes furthest from the release are with maximum slope gradients facing in the opposite direction of the mean aspect (α_{mean}) of the site.

The force and friction layers were combined to produce a unique composite force/friction layer for each site. Maximum run-out distance was set to 100 in the model to reflect the maximum possible combined value in the force/friction images. The dispersion value controls the degree to which the direction of force is allowed to deviate from the direction specified by aspect based on a Cosine function (Idrisi, 1987). Model results matched well with run-out areas mapped in the field and observed by other researchers with k set to 3 (e.g. Sah and Mazari, 1997; Tolia *et al.*, 1997) following several iterations of the model using values between 1.5 and 5. Figure 3.6 shows the locations of all landslides identified in the study area along with the modeled deposition areas.

The modeled deposition areas were reclassified and grouped using RECLASS and GROUP modules in Idrisi. Information on elevation, slope, aspect, proximity to streams/rivers, land use/cover type, and slope curvature was extracted for the release and deposition areas and entered into a hazards database for subsequent analysis of spatial patterns.

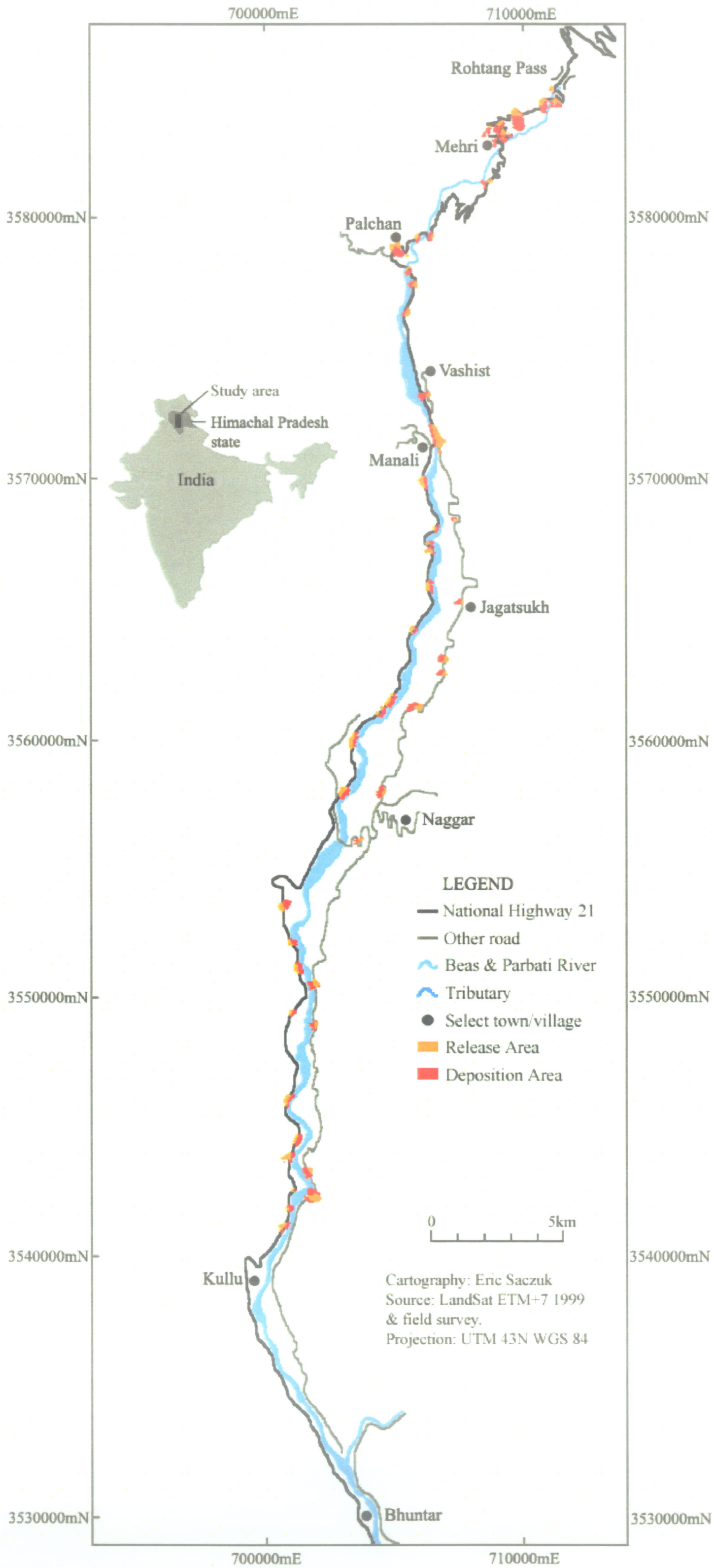


Figure 3.6 Release areas of all landslides identified during field surveys in 1999 and 2000 and their modeled deposition areas. (Author)

3.6.3 Debris Flows

Debris flows differ from landslides in that they are mostly confined to channels and involve the movement of material that has previously been deposited into the channel by other mass wasting processes or is entrained following erosion of the channel banks by the debris flow itself. Debris flow motion is typically initiated by a rapid influx of water into the *in situ* material which diminishes intergranular friction (i.e. its strength or resistance to deformation), increases the normal and shear stresses by adding weight to the mobilized material, and acting as a lubricant, especially when fine material such as clay is present. The flow of material may be rapid, interspersed by periods of no motion as debris dams build and are subsequently breached by the force of the built-up material or resaturated. Debris flows typically originate in steep, 1st order mountain channels that are typically v-shaped and lined with a mixture of coarse and fine inorganic and organic material (Figure 3.7). Evidence of debris flow activity in steep channels may include the presence of poorly and inversely sorted, matrix supported fan deposits, bouldery levees on top of steep channel banks, impact scars on trees in or near the channel, lack of living vegetation in the channel, and an ephemeral flow regime (Coussot and Meunier, 1996; Coussot, 1994; Brunsden, 1979). Culverts of the pipe or box type are often installed under roads in areas where debris flows have occurred frequently in the past and in some cases bridges are constructed over larger channels. The presence of these structures may indicate a history of debris flow activity, especially where these mitigative measures are new or have recently been upgraded or damaged. Twenty-three debris flow sites were identified in the field, and the average angle of their fans (10.2°) is in close agreement with results from previous research (4° – 18°) (Rowbotham and Dudycha, 1998; Jackson *et al.*, 1987; VanDine, 1985; Costa, 1984).

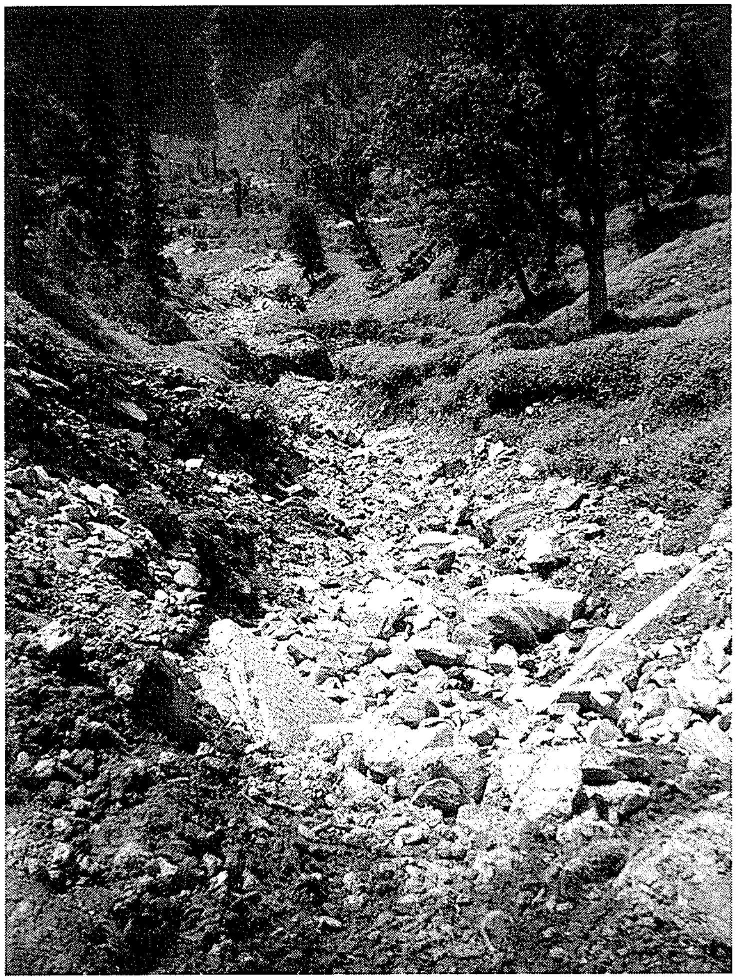


Figure 3.7 Debris flow channel incised into unconsolidated slope material. (Author, August 1999)

Although changes in various physical (eg. precipitation, temperature) and anthropogenic (e.g. land use/cover) factors may affect the frequency and magnitude of debris flow events, the main hazard area is the deposition zone near the channel mouth (van Steijn, 1996). Variables collected for each site at the intersection of the channel with a road include; (1) depth from the channel bed to the top of the bank or levee, (2) width between the tops of banks at 50, 100 and 150m upslope from the road intersection, (3) aspect of the channel and, (4) maximum diameter of the largest visible boulder measured using a measuring tape. The latter measurement, when multiplied by mean rock density, can be used to calculate unit weight of debris and estimate the magnitude of previous debris flow events (VanDine, 1985; Innes, 1983). An inclinometer was used to measure channel slope and a GPS recorded the elevation and position at the road/channel intersection.

Debris flow deposition zones were modeled using an anisotropic dispersion model (Equation 3) with layers showing starting locations, direction of dispersion and friction (Wise, 2000; Walker and Willgoose, 1999; Coe *et al.*, 1997; Hungr *et al.*, 1997; Chen, 1987).

$$Friction_i = \frac{(0.3(d_i)+1.3)+99e^{-0.0511(\beta_i)}+f\alpha_i}{3} \qquad (3)$$

Equation 3 is derived from equation 2 by adjusting the constants for maximum run-out distance and slope gradient to reflect actual conditions observed at 4 sites (see Equation 2 for explanation of variables). Maximum run-out distance in the model was set to 100 to reflect maximum possible cumulative friction. Maximum allowable dispersion, k, was set to 2.5 following several iterations during which k was varied between 1 and 5. The shape and size of 4 actual deposition areas surveyed in the field most closely matched modeled deposition with k = 2.5. The general shape of the modeled areas was also compared and matched well with results from Major (1997), who carried out extensive debris flow flume experiments to characterize debris flow deposition zones.Equation 3 represents the combined average friction value due to slope distance, slope gradient and slope aspect using the same variables as equation 2 but with modified constants based on the calibration of the equation to 4 debris flow deposition areas surveyed in the field.

Starting locations were defined by raster points as the locations at which the channel becomes unconfined, typically near road intersections or fan apex. In a few instances, debris flow channels crossed a road or were in close proximity to other structures at several locations along their lengths in which case the starting location was placed at the point where the channel was least confined. Aspect of the channel, measured with a compass, defined the direction of dispersion. Data on factors controlling debris flow activity including rate of erosion in the head region, size and land use/cover of the drainage basin, and stability of the channel banks, could not be collected due to monetary and time constraints. As a result, the model relied solely on downslope friction defined by equation 3 to estimate potential areas of deposition. The resulting debris flow deposition layer (Figure 3.8) was used to extract elevation, slope, aspect, and land use/cover information for each debris flow deposition area which was then entered into the hazards database.

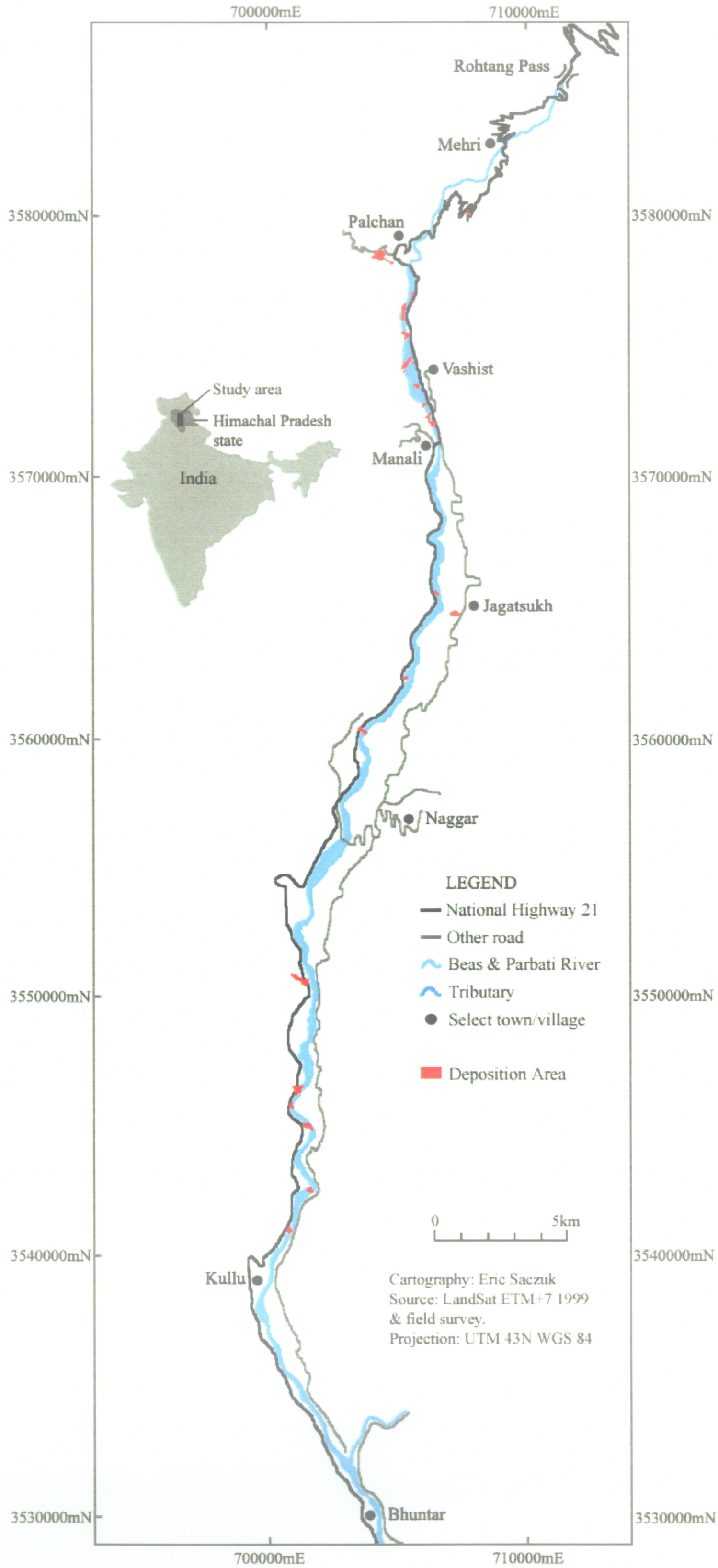


Figure 3.8 Modeled debris flow deposition areas. (Author)

3.6.4 Rock Fall

Locations of rock fall activity are characterized by steep, exposed cliffs of heavily fractured rock making them rather conspicuous in the field. Angular rock debris scattered around the base of a cliff is a primary indicator of previous activity. For the most part, these deposits accumulate by free fall directly from a weathering rock face. Rock fall particles do not subsequently under go mass movement as is the case for debris flows or landslides. The resulting talus accumulation is largely a consequence of individual clasts falling to the cliff base following its exposure due to a road cut. In some cases, rock fall has also occurred due to undercutting of the base of the face by fluvial action as well as on undisturbed slopes, perhaps due to earthquake activity. Inspection of the rock face can reveal signs of weakness such as wide (>5 mm), dense (<0.5 m apart) and continuous joints and fractures dipping out of the slope, water seeping out of the rock, and anomalous lichen growth (Rowbotham and Dudycha, 1998; Selby, 1980). The deposition zones of the relatively frequent, small-magnitude rock falls that tend to recur in this area are usually confined to the road surface, an adjacent ditch, or river bank. Historical records indicate that large magnitude rock slope failures have occurred here most frequently above tree line but also in the southern, lower parts of the valley. However, it is unlikely that subsequent failures of similar magnitude would soon recur at these sites as the main source of material had already been expended. Small magnitude failures may continue to occur but they are likely to exhibit behaviour similar to other low magnitude events.

Deposition areas were estimated in the field by taking into consideration the maximum potential volume of the release area based on the height and width of the rock face and morphological and topographic constraints downslope of the release site (Okura *et al.*, 2000). These estimates were reinforced by measurements of two actual rock fall deposition areas surveyed in the field which provided information on volume and deposition pattern of the material. Rock fall deposition areas were digitized on-screen as polygons adjacent to release areas based on these field observations and mapping of existing *in situ* deposits (Figure 3.9). Following the conversion of the deposition areas from vector polygons to a raster grid, information on elevation, slope, aspect, proximity to streams/rivers, and land use/cover was extracted from the factor layers and entered into the database.

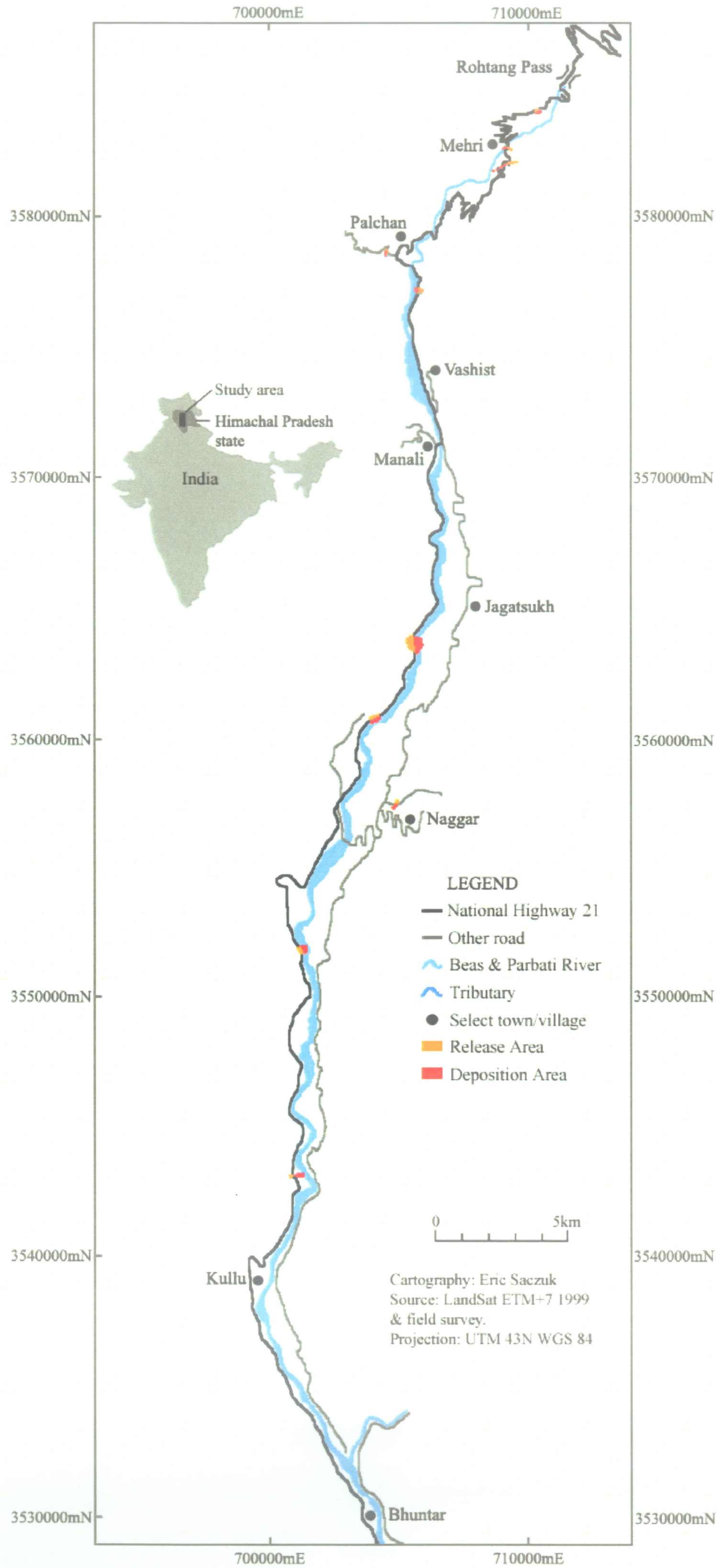


Figure 3.9 Distribution of rock fall release and deposition areas. (Author)

3.6.5 Flooding and Bank Erosion

Flooding and bank erosion are relatively frequent occurrences along the Beas River owing to the monsoon climate regime, steep channel gradient, high altitude and relief, and erodable bank material. Abundant runoff (885 mm y^{-1}) and rapid snow and ice melt in the spring coupled with steep, sparsely vegetated slopes in the head region create favorable conditions for large and potentially destructive floods. More than 10% of the total drainage area of 1,500 km^2 of the Beas River above Bhuntar is comprised of exposed, impervious bedrock which promotes rapid runoff and magnifies flood intensity. Also, most tributaries draining into the Beas River are 1st or 2nd order alpine channels that exhibit signs of flash flooding and in some cases debris flow activity. Bank erosion along these channels normally occurs during periods of flooding, as bank walls are undercut by turbulent waters; saturated ground conditions associated with flooding may help the bank failure process by reducing its strength.

Areas prone to flooding often are difficult to identify, especially in cases where the discharge characteristics of a river are widely variable, such as on the Beas River (Fekete *et al.*, 2002). Low-lying areas adjacent to the flood plain are obvious hazard sites, but others may include areas where; (1) the channel is confined, and an increase in discharge is compensated for by a dramatic rise in water depth, (2) areas consisting of highly erodable bank material susceptible to collapse or, (3) areas where natural or anthropogenic structures may cause water to pond or be diverted into settled regions. Some flood-prone areas and sites of bank erosion were identified in the field; in addition, a GIS-based flood model was employed to supplement the field observations and identify other less obvious areas of inundation and erosion (Blomgren, 1999; Thomas, 1987).

Flood modelling is a flexible and spatially accurate way of determining which areas may be affected by flooding and bank erosion. Although large-scale topographic maps (e.g. 1:10,000 or larger) may yield a reasonable estimate of the flood-prone area, a flood model can determine areas which may become inundated or subject to bank erosion by incorporating input data such as flow velocity, channel width and known, and predicted discharge values. The suitability and accuracy of a fluvial model depends heavily on the availability and quality of data about channel geometry, discharge values, surrounding topography, and the definition of exponents and coefficients in hydraulic geometry equations (Blomgren, 1999; Wohl, 1995). Three hydraulic geometry equations relate changes in discharge (Q) to changes in width (w), depth (d), and velocity (v) for open channel flow;

$$w = aQ^b \qquad (4)$$

$$d = cQ^f \qquad (5)$$

$$v = kQ^m \qquad (6)$$

where the exponents $b + f + m = 1$, and the coefficients $a \times c \times k = 1$ (Trenhaile, 1998). These equations are used to determine the responses in width, depth and velocity of water in the channel for each channel reach due to changes in discharge at-a-station or down slope. The exponentials define the rate of change (i.e. slope) of the hydraulic geometry equations with respect to changes in discharge. In most cases, an average exponent value based on known or estimated values of width, depth, velocity and discharge, is used for the entire river. However, given the variable character of a high energy stream like the Beas River, the exponents for several hundred unique reaches were derived using the techniques described below.

The methods used here are based on the Hydrologic Engineering Centers River Analysis System (HEC-RAS) developed by the U.S. Army Corps of Engineers (http://www.hec.usace.army.mil/software/hec-ras/hecras-hecras.html), which requires as input the cross-sectional geometry of the channel and flow rates in order to output flood water elevations using the HEC-GeoRAS extension to ArcView. A raster layer showing the planimetric profile of the Beas River and floodplain was constructed using a 1:50,000 scale land use zoning and flood protection map for a portion of the study area in conjunction with ETM7+ data. The land use zoning map showed the high flood level of the Beas River, areas of accelerated bank erosion and existing protection measures, all of which served as input into the flood model. However, the lack of sufficient topographic detail limited the performance of the inundation and bank erosion model. The ETM7+ data, which clearly show the channel and flood plain, were acquired in early October and thus represent mean or normal flow conditions (Fekete *et al.,* 2002). The river channel and floodplain were on-screen digitized and converted into separate raster layers with 30 m pixel resolution which, according to Walker and Willgoose (1999), is sufficient to extract stream networks, in order to provide the main input into the model. The river was then segregated into 975 unique reaches based on significant changes in floodplain width (>5 m in width over 50 m distance).

Accuracy of the rasterized planimetry of the river was checked at 5 locations in the field at which the width and depth were measured or known. An average width-depth channel ratio of 40 was established based on a measured range of between 36 and 52 at the 5 verified locations. Flow velocity for each section was computed using Manning's equation in order to establish flow velocities under normal flow conditions;

$$v = \frac{1}{n} \cdot R^{\frac{2}{3}} \cdot s^{\frac{1}{2}} \qquad (7)$$

where R is the hydraulic radius calculated as the cross-sectional area of the channel (w_{mean} x d_{mean}) divided by the wetted perimeter ($w_{mean} + 2d_{mean}$), s is slope of the channel, and n is Manning's roughness coefficient.

Slope was derived from the DEM by plotting elevation against distance from the channel head and ranged from 0.308 near Rohtang Pass to 0.013 at Bhuntar with several prominent nick points at Mehri, Bahang, and Dobhi where significant adjustments in slope profile are occurring. The extracted values coincided closely (R^2 = 0.88) to a vertical profile constructed by Sah and Mazari (1998). Manning's roughness coefficient is an element of resistance based on boundary conditions within and adjacent to the channel. This value is often derived from tables for a particular stream type given qualitative descriptions of channel shape, size of dominant bed material and extent of vegetation along the banks. According to Chow (1959 *in* Selby, 1985) Manning values for mountain streams with large boulders range from 0.04 to 0.07 and should be increased by up to 30% for winding sections. Working on ungauged mountain channels in Nepal, similar in nature to the Beas River, Wohl (1995) arrived at n values ranging between 0.06 and 0.09. A value of 0.072 was deemed appropriate for the Beas River, although a brief sensitivity analysis for values between 0.06 and 0.08 was carried out. Since the average width-depth ratio was determined as 40 and width is easily measured from the planimetric profile, Equation 7 can be expressed as;

$$v = \frac{1}{n} \cdot \left(\frac{w}{42}\right)^{\frac{2}{3}} \cdot s^{\frac{1}{2}} \qquad (8)$$

Following from this, discharge is the product of width, depth and velocity and can thus be expressed as;

$$Q = \left[\frac{1}{n} \cdot \left(\frac{w}{42}\right)^{\frac{2}{3}} \cdot s^{\frac{1}{2}}\right] \cdot \frac{w^2}{40} \qquad (9)$$

Velocity and discharge were calculated for each reach using width and slope layers as input. Actual mean discharge was known for two locations on the Beas River, namely upstream of the bridges at Manali and Bhuntar, and was in good agreement with computed values. Following aggregation of the 975 reaches into 8 sections according to a change in slope of 0.037, the hydraulic relationships between discharge, velocity, depth, and width were computed for each section. Discharge was plotted against width, depth and velocity yielding a power function describing the curve fit through the points for each section and generating the exponents and coefficients for Equations 4, 5 and 6. The near-perfect agreement between discharge and width, depth, and velocity (R^2 = 0.82 to 0.99) is mainly a result of width being included in the computation of depth, velocity and discharge. However, the velocity and discharge equations also include slope, width and Manning's *n* value as independent variables.

One of the main assumptions inherent in using the hydraulic geometry equations to predict changes in width, depth, and velocity in response to changes in discharge is that the exponents and coefficients for each variable being predicted remain constant as discharge changes. By knowning how width, depth and velocity may change in response to changes in discharge, it is possible to derive modeled values of width, depth and velocity based on predicted discharge values. This assumption holds for well confined reaches where the channel is not braided or where the floodplain is poorly developed. In other areas, particularly anastomosing reaches, the relationship between discharge and the hydraulic variables changes in response to changes in discharge. In light of this, the current inundation and erosion model is considered to be more accurate in areas where the Beas River is entrenched in a single channel with a small, well defined floodplain. These areas constitute approximately 50% of the entire length of the Beas River within the study area.

Sah and Mazari (1998) reported that the Beas River experienced a 7.7-fold increase in discharge at the Bhuntar gauging station from a low flow of approximately 300 $m^3 s^{-1}$ on 2nd September, 1995 to a maximum of 2,500 $m^3 s^{-1}$ between September 3rd and 6th. They also state that other destructive floods of similar magnitude were recorded in 1902, 1945, 1988, and 1993. The precise return period for this flood magnitude is difficult to establish, however monthly discharge data recorded at a gauging station at the mouth of the Beas River between 1968 and 1979 and compiled by Fekete *et al.* (2002) show that mean monthly discharge ranges from a minimum of 104 $m^3 s^{-1}$ in January to a maximum of 2,215 $m^3 s^{-1}$ in August with a mean discharge for the entire period of 497 $m^3 s^{-1}$. According to Fekete *et al.* (2002) discharge volumes on the Beas near the end of September or beginning of October correspond closely with mean or normal annual flow conditions. Based on this information, the response of the Beas River to a five-fold increase in discharge over the mean annual discharge was modeled, but the model is capable of computing the response in width, depth and velocity for any discharge.

Applying the hydraulic geometry equations in Idrisi generated new width, depth, and velocity layers showing the response of the channel to a 5-fold increase in discharge. The digital elevation model and the depth layer were then used to constrain the width layer such that given the water depth as shown on the modeled depth layer, the maximum possible width of the valley or flood plain for each reach was determined and if the modeled width exceeded this maximum value, the fringe areas were truncated on the width layer (Fig. 3.10).

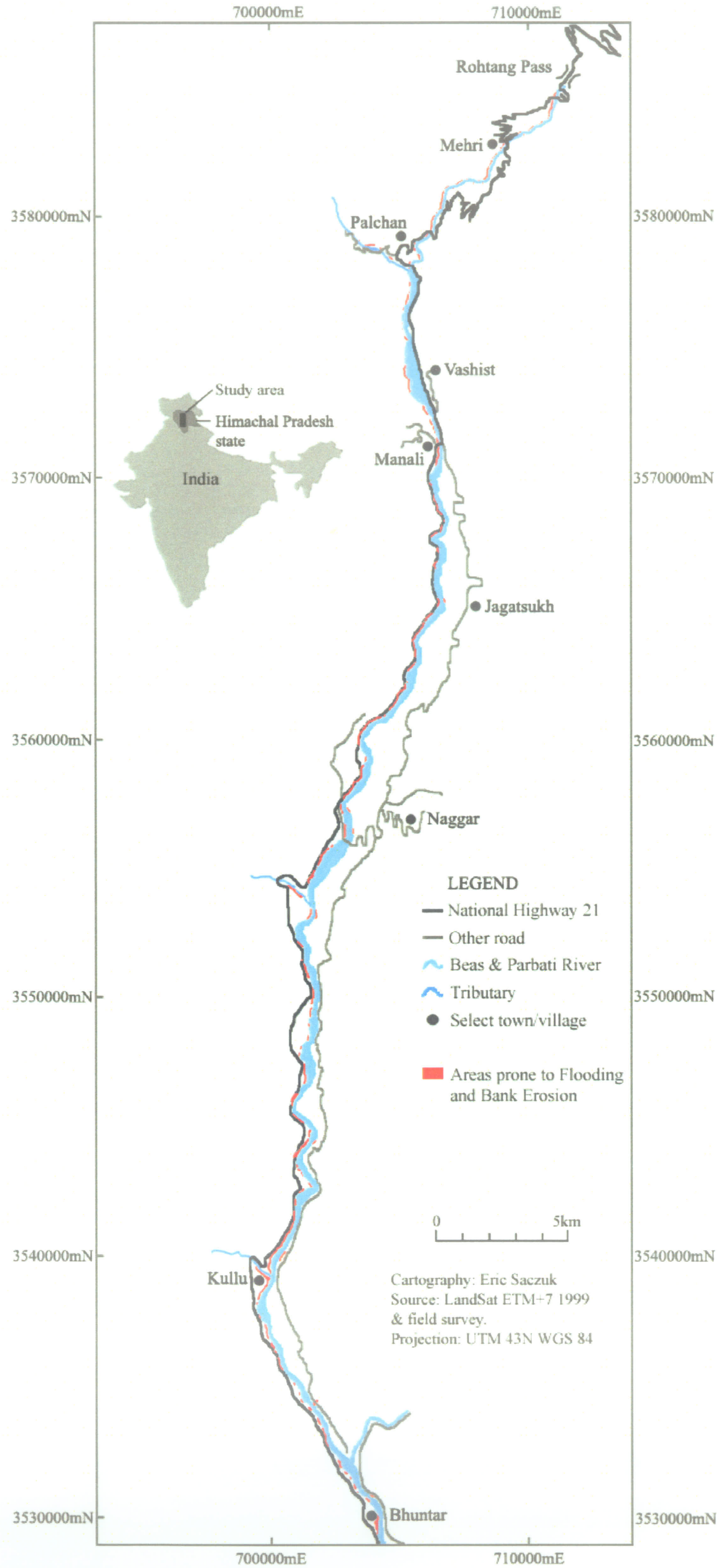


Figure 3.10 Predicted locations of inundation and bank erosion sites based on a 5-fold increase in discharge over mean flow conditions. (Author)

Sites displaying evidence of or potential for bank erosion were identified in the field and recorded on a map which was then digitized and converted to a GIS layer. The sites were identified on the basis of several criteria including evidence of undercutting and slumping of banks, extension of meanders to the edge of the floodplain, and the presence of control structures such as berms and concrete embankments (Figure 3.11). The original and accelerated velocity layers were also used to help identify other areas which may be susceptible to bank erosion due to accelerated water flow. The digitized bank erosion sites were buffered so as to extend them into the river channel and then used to extract velocity values from both the original flow and increased flow layers. Velocities for reaches where bank erosion is occurring were statistically compared to reaches not affected by stream erosion for both mean flow and flood conditions using a two-sample T-test.

Information for flood-prone areas and sites of bank erosion was extracted from each of the three time-series land use/cover maps and analyzed to determine the pattern of land use/cover change in areas affected by these geomorphic processes. A final inventory map was created by combining all surveyed and modeled release, deposition, inundation and bank erosion sites as shown in Figure 3.12.

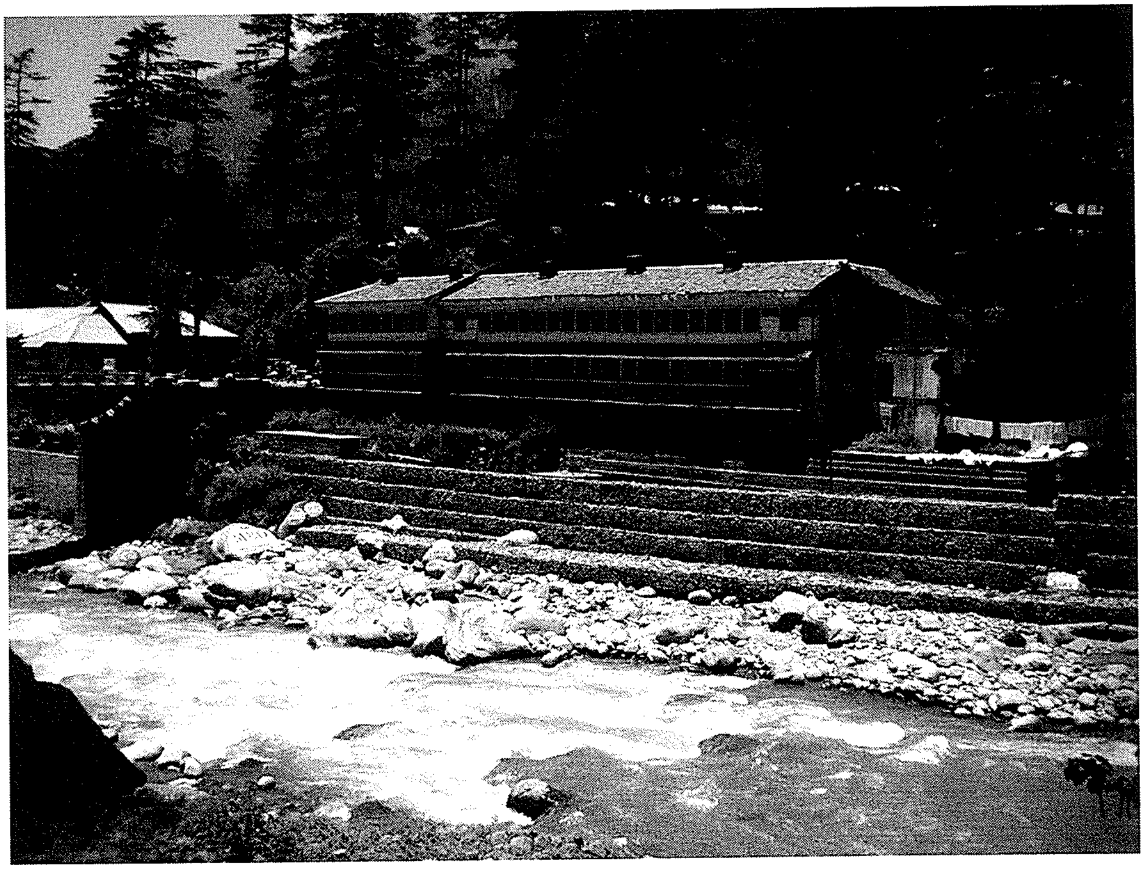


Figure 3.11 Bank reinforcement by rip-rap indicating previous bank erosion activity at Manali. (Author, June 1999)

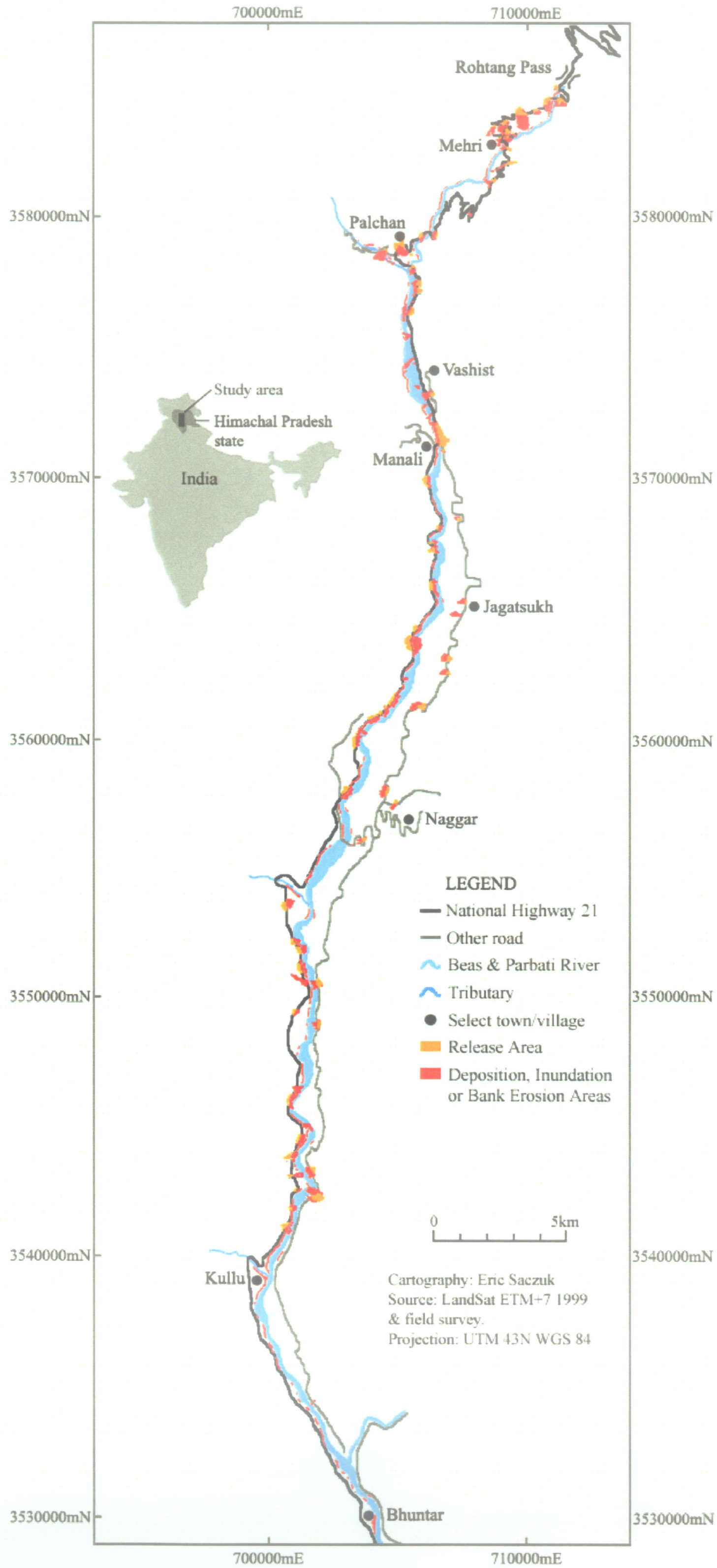


Figure 3.12 Locations of all hazard sites showing known release and modeled deposition, flooding and bank erosion sites. (Author)

3.7 Atmospheric and Seismic Factors

Precipitation is perhaps the most frequent triggering mechanism for a variety of geomorphic processes. The frequency and magnitude of geomorphic processes, including landslides, slumps, debris flows, rock fall, and floods, have been shown to increase with increases in the duration and/or intensity of precipitation events other factors being equal (Rebetez *et al.*, 1997; Baldwin *et al.*, 1987; Wieczorek, 1987; Gardner, 1983). Most research has demonstrated that regional denudation processes are more active during periods of intense and/or prolonged rainfall events assuming other factors such as seismic activity or slope gradient remain static.

Temperature changes also play a role in initiating denudation and mass wasting events. For example, gradual, long-term warming can accelerate glacial melt and increase runoff into river channels thereby increasing discharge and risk of flooding. Sudden increases in temperature on the other hand, may lead to rapid snow and ice melt and cause flash floods or debris flow activity over short periods of time. Changes in temperature or the frequency and intensity of precipitation events over a period of an hour, day, week, month, or year are reflected in a climate record for any given area.

Even with the avialability of hourly data, it is still extremely difficult to establish precipitation and temperature thresholds beyond which slope failure or flooding activity are likely to increase significantly due to the micro-variability of many influential factors such as geology, climate, topography, land cover/use, and surficial material type (Chen and Lee, 2002; Shroder Jr. and Bishop, 1998; VanDine, 1985). Thus for meso-scale studies, the relative changes in precipitation and temperature over time become more important than absolute threshold values in determining geomorphic activity.

A 98 year climate record (1901 – 1999), showing mean monthly precipitation, total annual precipitation, number of days of rain per month and total number of days of rain for each year collected at four stations in the viscinity of the Kullu Valley, namely Banjar, Kullu, Nagar and Keylong, served as input data into a statistical trend analysis (see Figure 2.1 and 4.14). The five rainiest months (January, February, March, July and August) were selected based on highest mean monthly rainfall and daily intensity and most number of days of rain per month. Specific variables analyzed were mean monthly precipitation, days of rain and average daily rainfall intensity. Changes in the 98-year trend of the above-mentioned precipitation variables were compared to mean values +/- 1 standard deviation in order to estimte what effects, if any, these changes may have had on the frequency and magnitude of landslide, debris flow, rock fall, flooding and bank erosion processes in the study area. Due to Government of India security restrictions, an adequate temperature record could not be obtained for the study area. The results of several previously published air temperature datasets recorded at Manali and Bhuntar are evaluated for the period 1968 to 1980.

Seismic activity, manifested as earthquakes, is also an important triggering mechanism of landslides and other slope failures (Owen *et al.*, 1995a; Barnard *et al.*, 1992). The Kullu Valley is situated in earthquake Zone V which encompasses areas of the highest earthquake magnitude and frequency (see Figure 2.4) (Chaudhury, 1995). Dozens of damaging earthquakes have been recorded in the Kullu Valley and surrounding areas as indicated by US Geological Survey data for an area bounded by

20°N – 37°N and 72°E – 82°E. A record of 1541 earthquakes between 1882 and 2004 is shown in Figure 2.4 and was analyzed for trends in frequency and magnitude. The mean magnitude of earthquakes occurring before and after 1963 (median year of the dataset) were statistically compared using a two-sample T-test for the period between 1882 and 2004. The problems associated with using earthquake frequency/magnitude data to analyze potential relationships between seismic activity and the occurrence of mass wasting and denudation events is discussed in detail in Section 2.1.2.

Chapter 4 Results and Discussion

4.0 Introduction

All of the landslide, rock fall and debris flow sites used in this analysis had either recently failed or showed potential for activity in the near future. For a period of time prior to their failure then, these sites represented potentially unstable slopes or areas that were prone to failure under the current state of geomorphic dynamic equilibrium (Kienholz *et al.*, 1984). The landslide and rock fall release areas identified in 1999 would likely be regarded as sites of potential slope instability if they had been identified in 1980 or 1972. They remained in a state of conditional stability until a triggering event of sufficient magnitude altered the major factors controlling the balance between resisting (shear strength) and driving (shear stress) forces leading to their failure. As already discussed in Sections 1.2.12, 1.2.1.3 and 1.2.2, the main factors predisposing a slope to instability include geology, slope, aspect and relief along with biophysical factors such as land use/cover and human activity.

Modeling deposition areas for sites that had recently failed allowed for a comparison of what could have been affected by these processes had they failed at some point in the past with what was actually affected as a result of their recent failure. Results from the GIS overlay and database analysis are presented for each hazard type in the subsections below. In the tables showing land use/cover change, the percent "change values" for the period 1972 to 1999 represent gross values and not the average of change between 1972 to 1980 and 1980 to 1999. Furthermore, the factor "change values" represent the factor by which land use/cover has changed for the given time period, with a value of 1.0 representing no change, values below 1.0 indicating a decrease in area and values above 1.0 represent an increase in area for the given land use/cover. The area of the 1972 land use/cover map is 255 km^2, while for 1980 and 1999, the area covered is 256 km^2 due to establishment of more roads after 1972.

4.1 Identifying, Mapping and Modeling Sites of Known Slope Instability and Denudation

The physical characteristics of landslide, debris flow, rock fall, flooding and bank erosion sites are presented below based on the extraction of information from input layers using Boolean masks of release and deposition areas through overlay analysis performed using GIS. These sites are identified in Figures 3.6, 3.8 and 3.9. The characterization of known hazard sites according to the input factors considered, serves as the starting point for a hazard susceptibility map for the region, and provides a strong basis for modeling and predicting other potential sites of mass wasting, erosion and denudation (Donati and Turrini, 2002). Release, deposition and inundation sites are discussed separately as applicable to each of the hazard processes considered.

4.1.1 Landslide Sites

The main characteristics of the 61 landslide *release* areas adjacent to paved roads in the Kullu Valley shown in Figure 3.6 are given in table 4.1 below. Landslide release areas cover 0.84% of the entire study area, are situated on mainly east-facing, moderately steep slopes and are in close proximity to streams. Most of the sites are uniformly distributed along 62 km of the 84 km-long valley with a distinct cluster within 4 km of Rohtang Pass where the steep, exposed slopes are particularly prone to intense physical weathering and mass movement (Figure 4.1).

Table 4.1 Landslide *release* area characteristics.

Factor	Value or Attribute	Min / Max
Total number of sites	61	N/A
Mean area of individual site	26,846 m^2	5,400 m^2 - 149,400 m^2
Total area of all sites	2,109,600 m^2	N/A
Mean relief	105 m	13 m – 328 m
Mean elevation	2,193 m	1,268 m - 4,037 m
Mean slope gradient	30°	16° - 54°
Dominant slope shape	Convex slopes	N/A
Dominant slope aspect range	89° - 137°, 247° - 282°	47° - 323°
Dominant land use/cover	Agriculture (41.4%)	N/A
Mean proximity to streams	310 m	70 m – 780 m
Proximity to Rohtang	30 km, 25% within 4 km	0.13 km – 62 km
Mean distance between sites [a]	4.0 km	N/A

[a] Distance between sites was determined for total length of all roads in the study area.

Figure 4.1 Typical surficial landslide release area adjacent to NH 21 near Rohtang Pass. (Author, August 1999)

Data on the size, total number of sites, and occurrences per kilometer of road of landslides indicate that they are spatially frequent and of low to medium magnitude, with an average of 1 landslide for every 4 km of road; only two sites exceeded 100,000 m^2 in area. Mean slope gradient (30°) is in close agreement with data collected by Deoja *et al.* (1991) who found that 90% of all landslides occur on gradients between 30° and 50° for similar areas in the Himalaya. Dominant aspect is directly related to the general north-south alignment of the valley and, consequently, with roads along which the landslides were surveyed.

The proximity of landslide-prone slopes to stream channels has been recognized as a factor in slope stability (Saha *et al.,* 2002). To test if this is also the case in the study area, the proximity to stream channels of 2344 randomly placed cells was statistically compared using an F-test to the proximity to stream channels of 2344 landslide-prone cells over the same geographic area. The results show that the two populations are statistically different with the landslide-prone cells more closely associated with stream channels than randomly selected points ($F = 2.79$, $f_{crit} = 1.37$, $P\text{-}Value \leq 0.0001$). This correlation between known landslides and their proximity to stream channels may be explained by the fact that water tables often are closer to the slope surface near stream channels which may in turn increase the pore-water pressure of the soil resulting in reduced cohesion, increased shear stress and a reduced factor of safety of the slope.

Landslide *deposition* areas as shown in Figure 3.6, were generated using an anisotropic friction model as described in detail in Section 3.6.2 and used to extract data from the factor layers in a GIS using Boolean overlay. Physical parameters that characterize landslide deposition areas are listed in table 4.2 below.

Table 4.2 Landslide *deposition* area characteristics.

Factors	Value or Attribute	Min / Max
Total number of sites	61	N/A
Mean area of individual site	81,720 m^2	9,900 m^2 - 350,100 m^2
Total area of all sites	4,576,500 m^2	N/A
Mean slope gradient	18.5°	4.6° - 34.5°
Dominant land use/cover	Settlements (55.3%)	N/A

Landslide *deposition* zones cover 1.8% of the total study area with high variability in the size of individual areas. They are predominantly located on gentle slopes which promote deposition and in the Settlement land use/cover category. Careful inspection reveals that more than half of the Settlement category affected by landslide deposition zones is comprised of roads with buildings and other human-built structures making up the rest.

4.1.2 Debris Flows

Debris flow *deposition* areas shown in Figure 3.8 and as discussed in Section 3.6.3, were generated using a variation of the anisotropic dispersion model used to model landslide run-out zones. Raster layers showing known or potential starting location, friction, direction and force of dispersion, maximum run-out distance, and maximum dispersion (k) served as input in the model. Table 4.3 below gives a summary of the characteristics of debris flow deposition zones in the Kullu Valley which were extracted using a Boolean mask of deposition zones from the slope gradient, land use/cover and roads layers.

Table 4.3 Debris flow *deposition* area characteristics.

Factors	**Value or Attribute**	**Min / Max**
Total number of sites	23	N/A
Mean area of individual site	54,081 m^2	3,600 m^2 - 174,600 m^2
Total area of all sites	1,189,800 m^2	N/A
Mean slope gradient	15.6°	1.3° - 62.8°
Dominant land use/cover	Settlements (55.7%)	N/A
Mean distance between sites[a]	10.0 km	N/A

[a] Mean distance between sites was determined for total length of all roads in the study area.

The 23 debris flows sites are located mainly between Mehri in the north and Kullu in the south, with several of the largest sites found near the confluence of the Beas River with the Solang River at Bahaang. Here, the Beas drains out of a deep, narrow rock-bound gorge and enters a wide, well developed floodplain. Tributary channels joining the Beas River are steeper and shorter in this section, providing a direct link between the erosion processes operating near the upper reaches of the steep basins and the river valley. The gross spatial frequency of debris flows found along paved roads is 1 site every 10 km. Approximately 0.5% of the study area is affected by debris flow activity with the mean individual deposition area covering just over 54,000 m^2 on predominantly gentle slopes (mean gradient of 15.6°) and in the settlement land use/cover category. Activity was directly observed at four of the sites during two field seasons and two additional failures were observed by other members of the research team. The remaining sites showed strong evidence of recent activity as discussed in Chapter 3, and were readily identifiable as being active.

4.1.3 Rock Fall

Ten rock fall *release* sites were identified in the Kullu Valley (see Figure 3.9), based primarily on the presence of steep, exposed rock cliffs adjacent to roads. Clear signs of recent activity such as coarse, lichen-free boulder deposits on or near the road at the cliff base were observed at several sites while the remainder showed strong evidence for future activity based on the presence of moisture seeping out of a dense network of joints and fractures, and converging planes of fracture (Figure 4.2). Table 4.4 summarizes the main characteristics of rock fall release areas derived from GIS layer overlays and field observations and measurements.

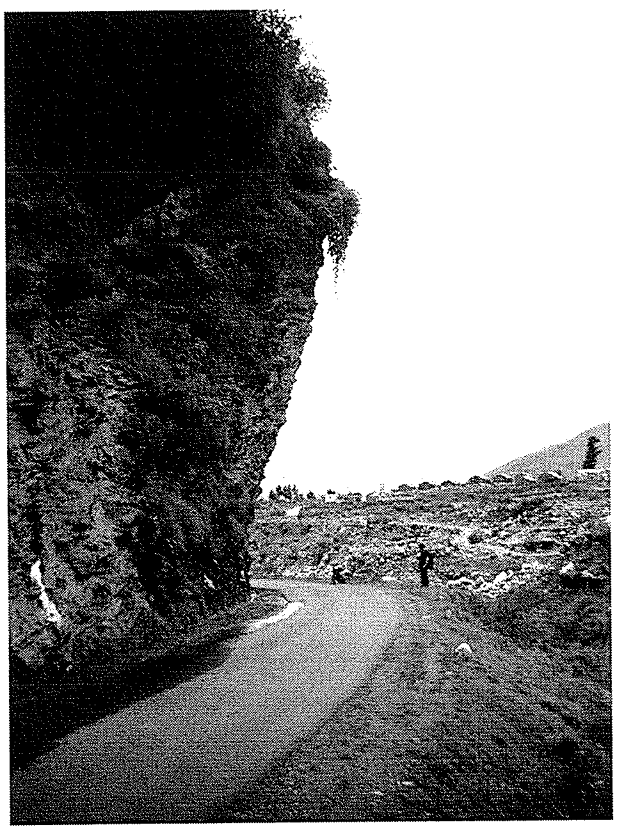


Figure 4.2 Over-steepened shale cliff with moisture seeping out of a dense network of joints and fractures. (Author, July 1999)

Table 4.4 Rock fall *release* area characteristics.

Factors	Value or Attribute	Min / Max
Total number of sites	10	N/A
Mean area of individual site	43,560 m^2	12,600 m^2 – 160,200 m^2
Total area of all sites	435,600 m^2	N/A
Mean relief	120 m	36 m – 309 m
Mean elevation	2,356 m	1,323 m - 3,781 m
Mean slope gradient	44°	32° - 65°
Mean slope aspect	70° - 170°, 230° - 300°	68° - 298°
Dominant land use/cover	Clearing (44.2%)	N/A
Mean proximity to streams	237 m	59 m – 551 m
Mean distance between sites [a]	0.04	N/A

[a] Mean distance between sites was determined for total length of all roads in the study area.

Rock fall *release* areas affect approximately 0.17% of the study area and form two loosely defined clusters; one 5 km to 20 km from Rohtang Pass in the north, and another between 35 km and 50 km from the Pass, in the vicinity of Naggar. Nine out of ten sites are less than 50,000 m^2 with only one large outlier with an area of 160,200 m^2. A weak relationship (R^2 = 0.6) between release area size and site aspect suggests that larger sites are found on mainly east to south-east facing slopes, while smaller sites occur on west to north-west facing slopes. It is difficult to offer additional insight into this apparent relationship since rock fall sites away from paved roads in the Kullu Valley were not surveyed, however the geologic asymmetry of the valley as mentioned in Section 2.1.1 may directly influence the distribution of rock fall sites in the study area. Based on field observations, most of the sites are not prone to frequent *en masse* failure of the entire slope, with the more common failure mechanism involving sporadic detachment of several blocks from the cliff and their subsequent break-up into smaller pieces upon hitting the ground. High mean slope gradient (44°) and dominance of the Clearing land use/cover category reflect the importance of these factors in the identification of potential rock fall sites in the field. Release areas were located closer to streams than randomly distributed pixels for the same geographical area and equal sample size ($F = 4.22$, $f_{crit} = 2.72$, $P\text{-}Value = 0.01$), which serves to reinforce the notion that the heightened ground water conditions found near stream channels are an important consideration in stability of rock slopes as well as slopes covered by surficial materials (as demonstrated for landslide release areas).

Potential rock fall *deposition* areas (see Figure 3.9) were manually on-screen digitized as discussed in Section 3.6.4. The dispersion model was not used for modeling rock fall deposition areas because firstly, the driving forces and frictions of large rock faces could not be adequately modeled in the GIS given the available data layers and, secondly, it was observed that in many cases the total volume of material deposited was a fraction of the total potential release area, which introduced an unacceptable level of complexity and uncertainty into the model. The deposition area layer was used to extract the characteristic variables listed in Table 4.5.

Rock fall *deposition* areas affect 0.22% of the study area with a majority of individual sites affecting an area less than 55,000 m^2 on low to moderate slopes. They are most frequently associated with the settlement land use/cover which consistently comprises over 50% of the area affected by rock fall deposition zones. Over 33% of the affected settlement area comprises of roads which underscores their ubiquitous function as deposition areas for a variety of mass movement phenomena, including rock fall.

Table 4.5 Rock fall *deposition* area characteristics.

Factors	Value or Attribute	Min / Max
Total number of sites	10	N/A
Mean area of individual sites	54,720 m^2	20,700 m^2 - 192,600 m^2
Total area of all sites	547,000 m	N/A
Mean slope gradient	20.4°	6.8° - 33.2°
Dominant land use/cover	Settlements (57.8%)	N/A

4.1.4 Flooding and Bank Erosion

A flood model was used to determine how changes in discharge affect the hydraulic geometry of the Beas River channel. More precisely, the aim was to quantify the response in channel width, depth, and velocity caused by a change in discharge given a set of initial channel parameters representing normal or low flow conditions. The response in width, depth, and velocity was modeled using hydraulic geometry equations (see Section 3.6.5) for 975 individual reaches of the Beas River. The results presented here are based on a five-fold increase in discharge over normal or mean annual flow conditions.

Mean channel width increased from 40 m to 70 m, when subjected to a 5-fold increase in discharge with local maximum increases of over 76 m in certain reaches. This translated into an increase in the planimetric area of the river surface from approximately 4 km^2 to over 7.8 km^2 over its length within the study area. Average flow depth increased from 0.8 m to 1.5 m with local maximum increases of 1.5 m over normal flow depths. Flood-prone areas are typically determined based on changes in width and especially depth so the modeled width and depth layers were combined to identify areas where flow height and width might be sufficient to cause flooding. Figure 3.10 shows that an area of 2.6 km^2 beyond bankfull stage would become inundated by flood waters given the modeled increase in discharge with most of that area consisting of Settlements (61.1%).

4.2 Land Use/Cover Change

Maps representing the distribution of 4 land use/class categories in the study area, namely Agriculture, Clearings, Forest, and Settlements for the years 1972, 1980 and 1999 were used to perform a pair-wise analysis of land use/cover change. Despite an effort to incorporate the 1920 land use/cover map, it was found that its areal coverage was insufficient to warrant further analysis. Inclusion of the historic land use/cover map reduced the dataset available for analysis below statistically acceptable levels. Thus, all subsequent land use/cover change comparisons are carried out using the 1972, 1980 and 1999 maps.

Land use/cover change for the periods 1972 to 1980 and 1980 to 1999 was analyzed for the whole study area as well as just in the areas affected by hazard processes. The changes presented below are expressed as the percent area of each category for each time period, the pair-wise change in percent area for each category and the factor by which each category has increased or decreased between each of the three time periods. The factor is computed by dividing the most recent percent coverage of a given category by the percent coverage of the same category from an earlier date, thus values greater than 1.0 represent an increase in percent coverage while values less than 1.0 represent a decrease. It is noteworthy that the results presented here reflect land use/cover changes in the study area and do not necessarily represent changes occurring in other parts of the Kullu Valley or Kullu District. Values in tables that are in bold font indicate the most significant changes (either highest or lowest), as applicable.

4.2.1 Land Use/Cover Change in the Study Area

The total area that has undergone land use/cover change remained relatively constant between the two time periods (26.2% between 1972 and 1980 and 26.6% between 1980 and 1999). The percent area of gross change over the entire study period (1972 – 1999) was 31.1%. Considering the number of years spanned by each time pair, the mean annual percent change declined from 5.4% to 2.4% for 1972 to 1980 and 1980 to 1999, respectively, based on a total study area of 256 km^2. Table 4.6 and Figure 4.3 below illustrate the general land use/cover changes between 1972, 1980 and 1999.

Table 4.6 Land use/cover change in the study area.

Land use/cover	**1972 (%)**	**1980 (%)**	**1999 (%)**	**% Δ '72–'80**	**% Δ '80–'99**	**% Δ '72-'99**	**Factor Δ '72–'80**	**Factor Δ '80–'99**	**Factor Δ '72-'99**
Agriculture	23.0	22.8	22.1	-0.2	-0.7	-0.9	1.0	1.0	1.0
Clearing	20.2	23.0	24.8	2.8	1.8	4.6	1.1	1.1	1.2
Forest	**50.1**	**46.5**	**43.1**	**-3.6**	**-3.4**	**-7.0**	0.9	0.9	0.9
Settlement	6.7	7.8	10.0	0.9	2.2	3.3	**1.2**	**1.3**	**1.5**

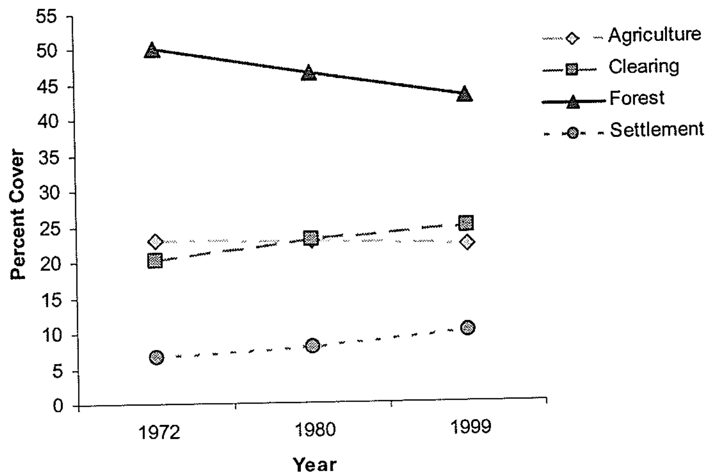


Figure 4.3 Land use/cover change for the entire study area between 1972 and 1999.

The main land use/cover changes affecting the entire study area between 1972 and 1999 are an increase in settlements by a factor of 1.49 and a decrease in forest cover by a factor of 0.86. Clearing areas have increased by a factor of 1.23 while agricultural land has declined slightly by a factor of 0.96. Both agriculture and forest appear to be changing at a fairly constant pace, whereas the expansion of settlements appears to be accelerating. These changes coincide closely with trends observed by other researchers who have noted a significant increase in infrastructure, a notable decrease in forest area, a slight decline in agricultural land and an apparent increase in clearing areas over the past 20 to 30 years (Gardner *et al.,* 2002; Joshi *et al.*, 2001; Gupta and Joshi, 1990; Singh, 1989). The expansion or intensification of infrastructure in mountainous areas has the potential to expose more people, their livelihoods and structures to naturally occurring processes of erosion and denudation. This increase in infrastructure, however, coupled with a general decrease in forest cover and an increase in clearing areas over the same time period significantly increases the potential for more frequent and/or more severe interactions between people and mass wasting activity. However, without considering how land use/cover has changed specifically in areas known to be affected by mass wasting and flooding activity, it is difficult to assess the degree to which these changes have altered the risk posed by erosion processes to the people and property in the Kullu Valley study area.

4.2.2 Land Use/Cover Change in Landslide Areas

Land use/cover and, consequently, stability, have changed in landslide release areas (see Figure 3.6) over the past three decades (Table 4.7). General land use/cover trends between 1972, 1980 and 1999 (Figure 4.4) show a steady increase in Agriculture and Settlements with a decrease in Forest cover and Clearings. Specifically, the most noticeable land use/cover changes in landslide release areas have been an increase in Agriculture by +17.6% since 1972 at an annual rate of +0.7% and a decrease of -13.5% in Forest at an annual rate of -0.5%. These trends indicate that some of the factors affecting slope stability in landslide release areas have been altered over the past 27 years owing to the removal of mature trees and the conversion of forests into agricultural fields (Sarkar *et al.,* 1995; Froelich and Starkel, 1993). This type of land use/cover conversion often results in increased surface runoff, greater exposure of soil to surface wash and erosion, increased normal stress due to weight of moisture in the soil, and decreased shear strength based on an increase in pore-water pressures (Saha *et al.*, 2002; Marston *et al.*, 1998). These main trends are marginally counteracted by a decline (-6.5%) in Clearings, which is considered the most erosion-prone category. The minor increase in Settlements (+2.3%) has a negligible impact on the stability of landslide release areas.

Table 4.7 Land use/cover change in landslide *release* areas.

Land use/cover	1972 (%)	1980 (%)	1999 (%)	% Δ '72–'80	% Δ '80–'99	% Δ '72-'99	Factor Δ '72–'80	Factor Δ '80–'99	Factor Δ '72-'99
Agriculture	23.8	**30.8**	**41.4**	**7.0**	**10.6**	**17.6**	**1.3**	**1.3**	**1.7**
Clearing	23.8	20.4	17.3	-3.4	-3.1	-6.5	0.9	0.8	0.7
Forest	25.6	21.6	12.1	-4.0	-9.5	-13.5	0.8	0.6	0.5
Settlement	**26.9**	27.2	29.2	0.3	2.0	2.3	1.0	1.1	1.1

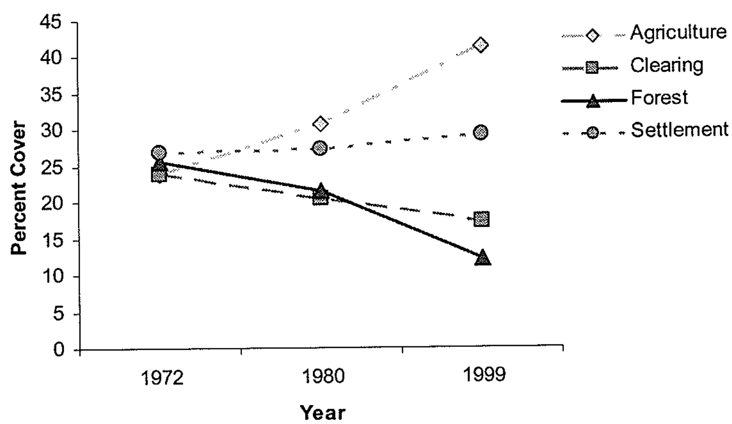


Figure 4.4 Land use/cover trends for landslide *release* areas between 1972 and 1999.

The land use/cover change results for landslide *release* areas indicate that the temporal and spatial frequency of these processes may be increasing based on the conversion of land use/cover from the most stable category (Forest) to one of lesser stability (Agriculture) (Blaschke *et al.*, 2000; Sarkar *et al.*, 1995). Without taking any other factors into consideration, this conversion could partly explain the transition of the *release* areas identified during the course of this research from potentially stable in 1980 or 1972 to actual failure sites in 1999 and 2000. Other factors which could significantly influence the temporal frequency of landslides such as the rate and intensity of weathering and the occurrence of triggering factors like intense rain events or earthquakes are considered later in this chapter.

Additionally, areas up to 500 m upslope of the actual release sites were analyzed because slope conditions immediately adjacent and upslope of the release site often strongly influence the stability of slopes directly below (Table 4.8). Results from this analysis point to a change in the factors affecting slope stability (Figure 4.5). Dominant changes between 1972 and 1999 include a decrease in Forest (-10.0%) and an increase in Clearings (+5.9%) which represent a general conversion from the most stable category (Forest) in 1972 and 1980 to the least stable category (Clearings) in 1999. The removal of mature trees upslope of the release area increases the erosion potential of the slope through the mechanisms discussed above and represents further evidence that the temporal frequency and spatial density of landslides in the study area may have increased since 1972. The negligible change in Agriculture (+0.1%) and the minor increase in Settlements (+4.0%), which cover a significantly smaller proportion of the area compared with the release areas themselves, have likely had little effect on landslide activity over the past 27 years.

Table 4.8 Land use/cover change immediately upslope of landslide release areas [a].

Land use/cover	1972 (%)	1980 (%)	1999 (%)	% Δ '72–'80	% Δ '80–'99	% Δ '72-'99	Factor Δ '72–'80	Factor Δ '80–'99	Factor Δ '72-'99
Agriculture	32.1	25.4	**32.2**	-6.7	**6.8**	0.1	0.8	1.3	1.0
Clearing	20.3	30.1	26.2	**9.8**	-3.9	5.9	**1.5**	0.9	1.3
Forest	**38.6**	**35.4**	28.6	-3.2	-6.8	**-10.0**	0.9	0.8	0.7
Settlement	9.0	9.1	13.0	0.1	3.9	4.0	1.0	**1.4**	**1.4**

[a] Land use/cover upslope was determined for a buffer zone 500 m above the release area.

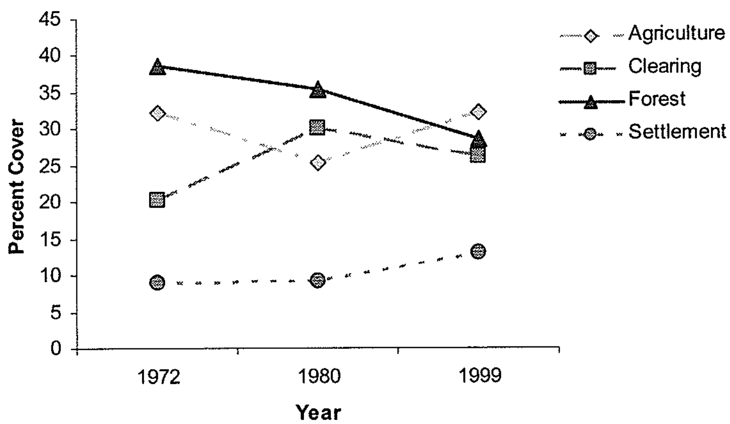


Figure 4.5 Land use/cover trends for areas immediately upslope of landslide release areas between 1972 and 1999.

The main land use/cover changes in landslide *deposition* zones (see Figure 3.6) between 1972 and 1999, are a steady increase in Settlements (+11.6%), a net decrease in Agriculture (-7.5%), a slight decrease in Forest (-2.3%) with little change (-1.8%) in the Clearings category (Table 4.9 and Figure 4.6). From the perspective of natural hazards and susceptibility, the most important land use/cover change in landslide *deposition* areas is the significant increase in Settlements. In fact, Settlements represent the single largest land use/cover category in landslide *deposition* areas for each of the three time periods meaning that the risk posed by these processes to structures and the people who use them has been persistent throughout the entire time span of this study. Perhaps more importantly however, risk appears to have steadily increased as a result of continued development in deposition areas. The destruction of dozens of kilometers of highway NH 21 and the left bank road between Rohtang Pass and Bhuntar over the past several decades (Sah and Mazari, 1998; Gardner *et al.*, 1997) attests to the vulnerability of the population of the Kullu Valley to these processes. Many attempts have been made to stabilize slopes that have previously failed or are suspected of sliding using concrete berms, gabion baskets or retaining walls. In many cases, however, the surficial material, which is continuously accumulating on the slope, remobilizes and overruns or destroys the mitigative structure within a short period time (see Figure 3.5).

Table 4.9 Land use/cover change in landslide *deposition* areas.

Land use/cover	**1972 (%)**	**1980 (%)**	**1999 (%)**	**% Δ '72–'80**	**% Δ '80–'99**	**% Δ '72-'99**	**Factor Δ '72–'80**	**Factor Δ '80–'99**	**Factor Δ '72-'99**
Agriculture	33.4	20.6	25.9	**-12.8**	5.3	-7.5	0.6	**1.3**	0.8
Clearing	5.0	10.0	3.2	5.0	-6.8	-1.8	**2.0**	0.3	0.6
Forest	17.9	21.1	15.6	3.2	-5.5	-2.3	1.2	0.7	0.9
Settlement	**43.7**	**48.4**	**55.3**	4.7	**6.9**	**11.6**	1.1	1.1	**1.3**

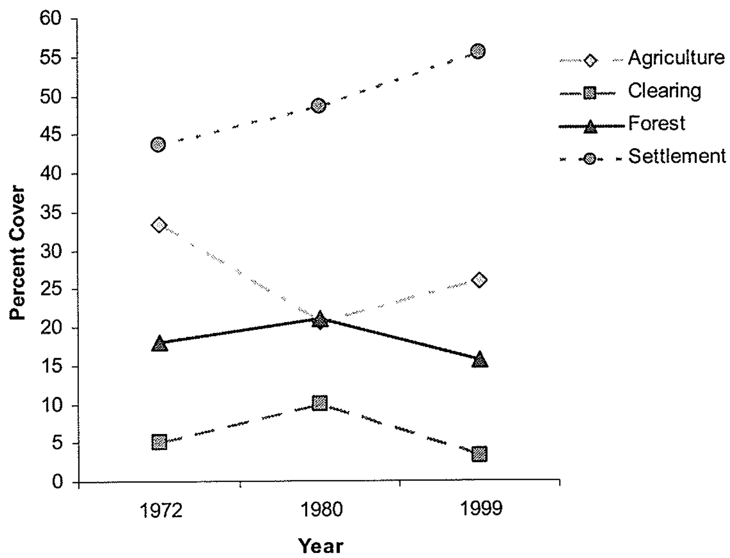


Figure 4.6 Land use/cover trends for landslide *deposition* areas between 1972 and 1999.

4.2.3 Land Use/Cover Change in Debris Flow Deposition Areas

According to model results and direct observations, most of the material mobilized by debris flows is deposited either onto the floodplain or directly into the Beas River with the remainder predominantly affecting Settlements and Agriculture fields (see Figure 3.8). The area of Settlements affected by debris flow activity has increased by +27.4% between 1972 and 1999 (Table 4.10) and this is the only land use/cover trend that appears to have increased steadily over the period of study (Figure 4.7). This increase in Settlements is directly related to the expansion and intensification of human infrastructure into geomorphologically unstable areas as discussed in Section 2.2.6. Furthermore, with roads removed from the Settlements category, the area of debris flow-prone settlements increases by +28.5% during the same time period, suggesting that buildings and other infrastructure, not roads, account for much of the increase in susceptibility of settlements to this type of hazard. The overall trend in Agriculture areas affected by debris flows is a decrease of -11.8% between 1972 and 1999. However, the period between 1980 and 1999 shows an increase in the area of +14.3%. This is likely a reflection of the general pattern of abandonment of agricultural fields prior to 1980 due to the overall decline in the interest of the newer generations in farming. Some slopes may have began to revert to forest cover prior to 1980 as evidenced by the corresponding increase in Forest of +9.0% during this time period, followed by a subsequent decrease in Forest (-18.7%) between 1980 and 1999, which coincides with renewed interest in farming in the form of horticulture and orchardry which are regarded as more sustainable and economically viable than traditional farming (Singh, 1989). Clearings have steadily declined by 5.9% between 1972 and 1999 and they represent the smallest proportion of land affected by debris flows. This is expected since Clearings tend to be located at higher elevations than most debris flow deposition areas.

Table 4.10 Land use/cover change for debris flow deposition areas.

Land use/cover	**1972 (%)**	**1980 (%)**	**1999 (%)**	**% Δ '72–'80**	**% Δ '80–'99**	**% Δ '72-'99**	**Factor Δ '72–'80**	**Factor Δ '80–'99**	**Factor Δ '72-'99**
Agriculture	**45.1**	19	33.3	**-26.1**	14.3	-11.8	0.4	**1.8**	0.7
Clearing	6.3	6.2	0.4	-0.1	-5.8	-5.9	1.0	0.1	0.1
Forest	20.3	29.3	10.6	9.0	**-18.7**	-9.7	1.4	0.4	0.5
Settlement	28.3	**45.2**	**55.7**	16.9	10.5	**27.4**	**1.6**	1.2	**2.0**

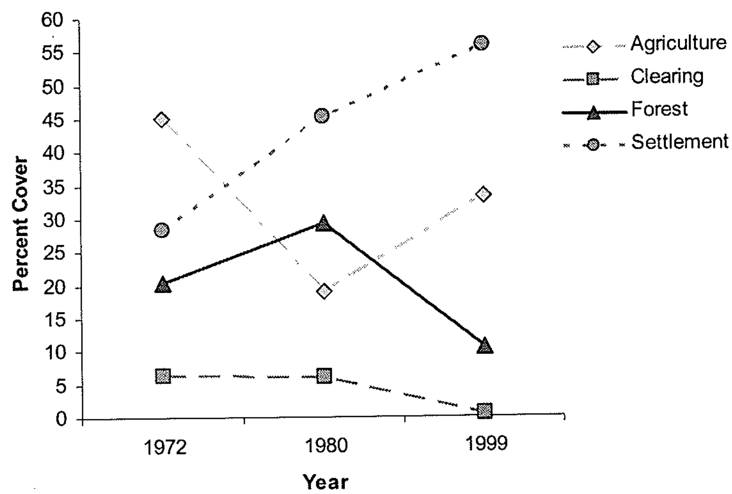


Figure 4.7 Land use/cover trends for debris flow deposition areas between 1972 and 1999.

Many destructive debris flows have been recorded in this area over the past several decades including an event in August 1999, which destroyed 15 homes and caused 7 fatalities near Jagatsukh (Figure 4.8). In this case, there was little prior evidence to suggest that the channel was prone to debris flow activity apart from a steep channel gradient near the head and a high basin relief ratio.

Figure 4.8 Debris flow through a village near Jagatsukh in 1999. (Bingeman, September 1999)

This serves as an example of a temporarily inactive or dormant site which may fail under unique circumstance such as high channel loading coupled with an exceptional triggering event (extremely intense, isolated rainstorm, in this case) (Neary and Swift, 1987). Often the bulk of the material involved in a debris flow is entrained from the channel bed and banks along with organic matter as a result of bank scour and slumping (VanDine, 1985). Land use/cover change, particularly deforestation in the head regions or along the banks of the debris flow channel could increase runoff and sediment delivery into the channels resulting in faster loading of debris into the channels and an increase in their response to precipitation and melt events which would ultimately promote more frequent failures (D'Agostino and Marchi, 2001).

There are no adequate structures which could fully mitigate the risk posed by debris flows in the study area (Okuda *et al.*, 1980). Despite the construction of concrete culverts and even bridges over two of the channels, it is obvious that they were designed for maximum fluvial discharge conditions and not debris flow discharge volumes, which can be several orders of magnitude larger (Costa and Jarrett, 1981). Ample evidence of clogged culverts, bridges damaged by boulders and trees, and over-bank and over road debris flow deposits is documented by Ghilardi *et al.* (2001) and was observed directly during the two field surveys. Access to equipment with which to periodically excavate debris flow channels in order to accommodate future events is limited. Elaborate and temporary storage systems or channel adjustment works are beyond the financial means of the local government and other stakeholders, as is often the case in the mountain regions of developing countries. Cost-effective mitigation of debris flow hazards requires knowledge and recognition of factors which may lead to failure at a site and a periodic check of these factors at known or suspected sites. An initial inventory of potentially hazardous sites, such as is presented here, is the basis for subsequent periodic checks which involve visually or quantitatively assessing the degree of loading at each site, based on an estimate of channel depth relative to bank height, noting signs of recent activity such as fresh levees, or inversely sorted matrix supported deposits, indicating a non-fluvial, gravity-controlled depositional environment, and keeping track of precipitation amounts and rates (Saczuk and Gardner, 1998). In an area such as the Himalaya, sediment delivery rates are high owing to extremely high rates of denudation in the upper elevations (7 mm kya^{-1}), which ensures a continuous supply of material into active debris flow channels. Although monsoon rains are known to trigger debris flows, a better understanding of the relationship between intensity and duration of rain events and debris flow activity is required in order to accurately predict the timing of failure events at any given site (Wieczorek, 1987).

4.2.4 Land Use/Cover Change in Rock Fall Areas

Rock fall *release* areas (see Figure 3.9) are closely associated with Clearings, which, as discussed in Sections 1.2.2.5 and 1.2.3.4, represent the lowest relative slope stability class (Table 4.11 and Figure 4.9). Recall that Clearings are comprised mainly of sparsely vegetated slopes, grazing areas, abandoned lands, and rock outcrops, so the dominance of this category in areas prone to rock fall hazard is expected (see Section 2.1.4). The noticeable decline in Clearings (-7.6%) between 1972 and 1999 in rock fall *release* areas appears to be countered by a sharp increase (+18.7%) in Agriculture area over the same time period. The presence and decline of Settlements (-2.6%) and Forest (-11.5%) in these areas is most likely due to the location of houses and tree stands in very close proximity to the rock cliffs including on top of the rock faces. Despite the decrease in Clearings, these land use/cover trends may have had an impact on predisposing factors controlling slope stability in rock fall release sites owing to the potentially higher infiltration rates in areas that have been deforested or converted to agricultural activity which may lead to more frequent and/or pronounced freeze-thaw cycles or result in higher hydrostatic pressures within the rock.

Table 4.11 Land use/cover in rock fall *release* areas.

Land use/cover	1972 (%)	1980 (%)	1999 (%)	% Δ '72–'80	% Δ '80–'99	% Δ '72-'99	Factor Δ '72–'80	Factor Δ '80–'99	Factor Δ '72-'99
Agriculture	13.0	15.9	31.7	2.9	**15.8**	**18.7**	**1.2**	**2.0**	**2.4**
Clearing	**51.8**	**50.8**	**44.2**	-1.0	-6.6	-7.6	1.0	0.9	0.9
Forest	16.1	10.6	4.6	**-5.5**	-6.0	-11.5	0.7	0.4	0.3
Settlement	22.1	22.8	19.5	0.7	-3.3	-2.6	1.0	0.9	0.9

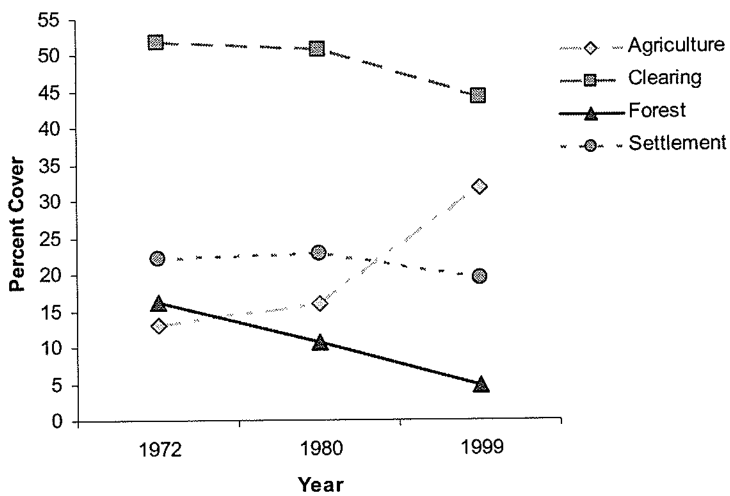


Figure 4.9 Land use/cover trends for rock fall *release* areas between 1972 and 1999.

An examination of the land use/cover changes in areas within 500 m of rock fall release areas (Table 4.12 and Figure 4.10) reveals some changes in the land use/cover categories between 1972 and 1999. Clearings and Settlements appear to have increased by +5.5% and +2.3%, respectively countered by decreases of -1.8% and -6.1% in Agriculture and Forest, respectively. Although the changes between 1972 and 1999 are fairly minor, the main shift from Forest cover to Clearings in areas that strongly influence the stability of rock slopes may have affected the intensity of weathering processes which directly control rock fall activity along the main roads in the study area. The removal of mature trees can potentially lead to accelerated soil erosion in areas upslope allowing moisture to rapidly infiltrate into the rock slope through exposed joints and fractures, thus promoting more frequent freeze-thaw cycles, accelerating the physical break-down of the rock face.

Table 4.12 Land use/cover change within 500 m of rock fall release areas.

Land use/cover	1972 (%)	1980 (%)	1999 (%)	% Δ '72–'80	% Δ '80–'99	% Δ '72-'99	Factor Δ '72–'80	Factor Δ '80–'99	Factor Δ '72-'99
Agriculture	24.1	24.5	22.3	0.4	-2.2	-1.8	1.0	0.9	0.9
Clearing	**30.9**	**33.1**	**36.4**	2.2	3.3	5.5	**1.1**	**1.1**	**1.2**
Forest	27.6	25.2	21.5	**-2.4**	**-3.7**	**-6.1**	0.9	0.9	0.8
Settlement	17.4	17.2	19.7	-0.2	2.5	2.3	1.0	**1.1**	1.1

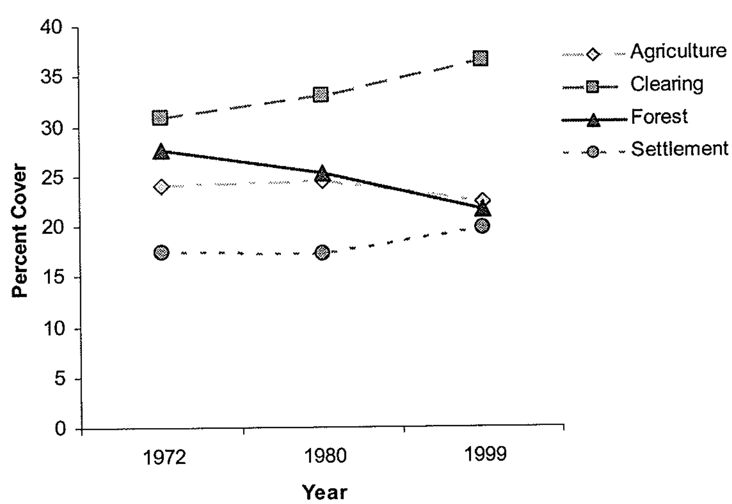


Figure 4.10 Land use/cover trends in areas adjacent to rock fall release sites between 1972 and 1999.

Land use/cover changes in rock fall *deposition* zones between 1972 and 1999 are characterized by declining Forest cover (-14.5%) and an increase in Agriculture and Settlements (+8.5% and +6.2%, respectively) (Table 4.13). The potential for damage to infrastructure and livelihoods and the related economic and human losses is generally much greater in areas of Agriculture and Settlements than in areas of Forest. The expansion and intensification of human-built structures into hazardous, geomorphologically sensitive areas, such as rock fall *deposition* zones is another example of how risk has increased in the study as a result of poorly planned development and a lack of awareness of potential sites of slope instability. Rock fall areas do not affect Clearings at all which, as discussed previously, tend to be located upslope from most of the *deposition* areas studied here.

Table 4.13 Land use/cover change in rock fall *deposition* areas.

Land use/cover	**1972 (%)**	**1980 (%)**	**1999 (%)**	**% Δ '72–'80**	**% Δ '80–'99**	**% Δ '72-'99**	**Factor Δ '72–'80**	**Factor Δ '80–'99**	**Factor Δ '72-'99**
Agriculture	20.8	21.5	29.3	0.7	7.8	8.5	**1.0**	**1.4**	**1.4**
Clearing	0.0	0.0	0.0	0.0	0.0	0.0	n/a	n/a	n/a
Forest	27.6	24.8	13.1	**-2.8**	**-11.7**	**-14.5**	0.9	0.5	0.5
Settlement	**51.6**	**53.7**	**57.8**	2.1	4.1	6.2	**1.0**	1.1	1.1

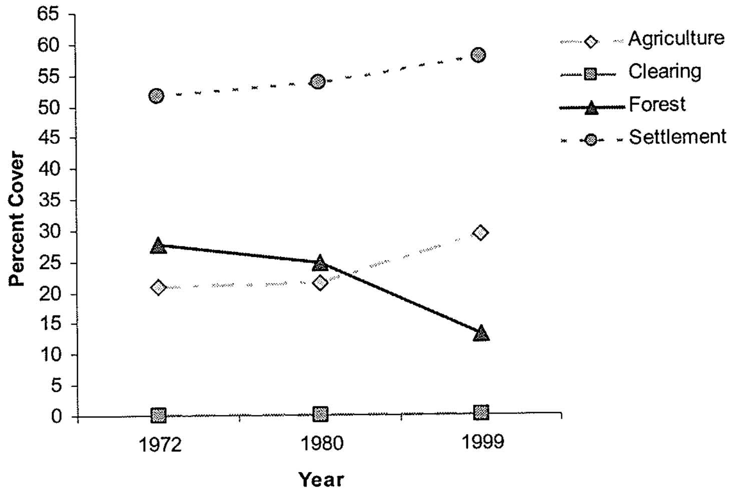


Figure 4.11 Land use/cover trends in rock fall *deposition* areas between 1972 and 1999.

Several mitigation techniques can be effective in reducing risk from rock fall. Some less costly options include installation of steel nets to prevent direct deposition of rock material onto road surfaces or nearby structures, installation of drain pipes into the cliff face to reduce pore-water pressure, and managing lands adjacent to the release area to ensure a sufficient vegetative cover is maintained and soil erosion is restricted to a minimum under the current land use/cover. Ultimately, however, it may be necessary to prohibit the construction of any structures except roads adjacent to rock cliffs which show strong potential for future failure.

4.2.5 Land Use/Cover Change in Areas Affected by Flooding and Bank Erosion

Areas prone to flooding and bank erosion were generated using a discharge model as discussed in Section 3.6.5 (see Figure 3.10). These areas were converted to a Boolean mask and subsequently used to extract land use/cover information from the 1972, 1980, and 1999 maps in order to assess changes in land use/cover given a flood magnitude 5 times normal flow conditions (Table 4.14 and Figure 4.12). GIS overlay results show that Forest and Settlements account for most of the area affected by floods (over 80% for each of three time preiods). Settlements are located predominantly near the valley bottom, thus the dominance of this land use/cover category in the in areas affected by flooding in 1999 is not unexpected. However, the extent of Forest area affected by floods, particularly in 1972 and 1980, required further interpretation. Detailed inspection of the distribution of flood-prone areas revealed that isolated forest stands adjacent to the floodplain were more extensive than agricultural fields, which were located higher up the slope on top of alluvial fans, above the floodplain proper. These results are alarming given the history of large destructive floods on the Beas River and the recent loss of human life and infrastructure (Gardner *et al.*, 2002; Sah and Mazari, 1998). It is probable that unless a serious and concerted effort is made to update and enforce the existing zoning laws, control and monitor the issuance of building permits, and upgrade or realign NH 21 in a few key sections, the human and monetary losses due to floods will increase dramatically in the Kullu Valley in the forseeable future.

Table 4.14 Land use/cover changes in flood-prone and bank erosion areas.

Land use/cover	**1972 (%)**	**1980 (%)**	**1999 (%)**	**% Δ '72–'80**	**% Δ '80–'99**	**% Δ '72-'99**	**Factor Δ '72–'80**	**Factor Δ '80–'99**	**Factor Δ '72-'99**
Agriculture	10.5	9.0	9.7	-1.5	0.7	-0.8	0.9	1.1	0.9
Clearing	7.2	6.6	1.0	-0.6	-5.6	-6.2	0.9	0.2	0.1
Forest	**51.3**	**48.0**	28.2	-3.3	-19.8	-23.1	0.9	0.6	0.5
Settlement	31.0	36.4	**61.1**	**5.4**	**24.7**	**30.1**	**1.2**	**1.7**	**2.0**

Total area affected by flooding and bank erosion = 7.8 km^2

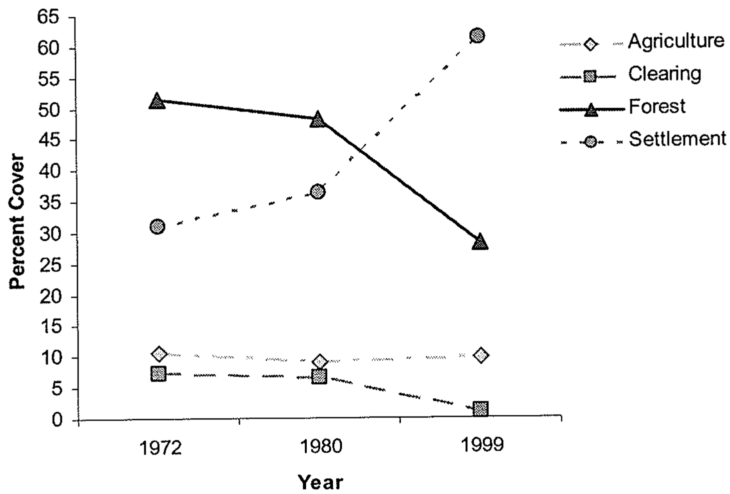


Figure 4.12 Land use/cover trends in areas affected by flooding and bank erosion between 1972 and 1999.

Field observations of bank erosion sites indicate that these areas are often found in confined river sections, where changes in discharge are strongly reflected in changes in flow velocity. The locations of bank erosion sites identified during the field surveys were compared with layers of normal flow velocity and accelerated flow velocity due to a 5-fold increase in discharge. No correlation between either of the two velocity layers and sites of known bank erosion was found. Subsequently, a derivative layer was generated by subtracting the velocity layer under flood conditions from the velocity layer under normal flow conditions. This derivative velocity layer was then compared with the locations of bank erosion sites. Results show that the difference in water velocity between normal and flood conditions is significantly greater in channel sections where bank erosion is known to occur (v_{mean} = 1.2 m s^{-1}) compared with reaches identified as stable (v_{mean} = 1.0 m s^{-1}) (*t-Stat* = 4.32, t_{crit} = 1.65, *P-Value* $\leq$ 0.000 at 0.05 C.I.). Most bank erosion sites identified in the field correspond to areas of significant velocity increase (2 m s^{-1} or more) during flood conditions over normal flow rather than simply areas of maximum velocity. A number of new sites were found and added to the bank erosion hazards layer. The flood buffer and bank erosion layers were combined to create a composite fluvial hazards layer which was used to extract the data shown in Table 4.14 and Figure 4.12 above.

4.2.6 Land Use/Cover Change in All Hazard Areas Combined

Land use/cover changes for each individual hazard type were discussed in sections 4.2.1 through 4.2.5 above. The aim of this section is to present the land use/cover changes for all deposition and inundation areas combined. All *deposition* zones for landslides, debris flows and rock fall sites as well as areas affected by inundation due to flooding and bank erosion were combined into a single Boolean mask which was used to extract the land use/cover information from the 1972, 1980 and 1999 land use/cover maps shown in Table 4.15 and Figure 4.13 below. The results reveal how the exposure of people and property, in these high risk zones, has changed and provides the basis for an evaluation of susceptibility.

Table 4.15 Land use/cover changes in all *deposition* areas.

Land use/cover	1972 (%)	1980 (%)	1999 (%)	% Δ '72–'80	% Δ '80–'99	% Δ '72-'99	Factor Δ '72–'80	Factor Δ '80–'99	Factor Δ '72-'99
Agriculture	24.9	15.3	20.4	**-9.6**	5.1	-4.5	0.6	1.3	0.8
Clearing	2.6	2.6	0.9	0.0	-1.7	-1.7	1.0	**0.4**	0.4
Forest	37.1	42.4	26.1	5.3	**-16.3**	-11.0	**1.1**	0.6	0.7
Settlement	35.4	39.7	52.6	4.3	12.9	**17.2**	**1.1**	1.3	**1.5**

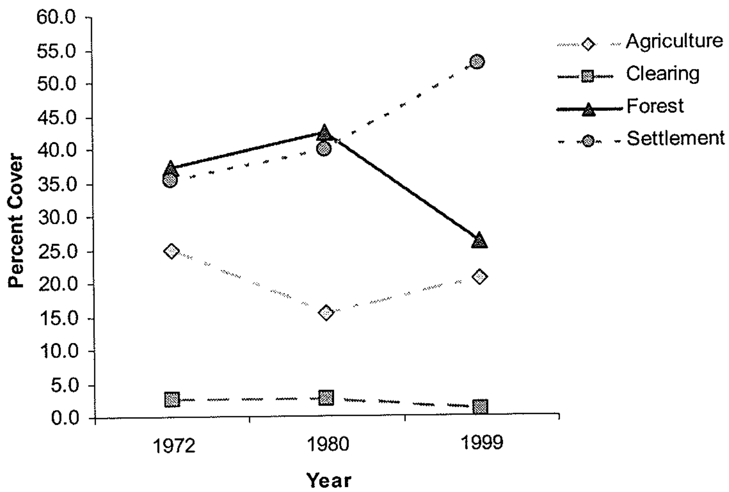


Figure 4.13 Land use/cover trends in all *deposition* areas between 1972 and 1999.

Land use/cover changes between 1972 and 1999 in all *deposition* are characterized by a steady increase in the area of Settlements (+17.2%) and a decline in Forest (-11.0%), Agriculture (-4.5%) and Clearings (-1.7%). These net trends however conceal the significant fluctuations in land use/cover between 1972 and 1980 and 1980 and 1999. The apparent decline in Agriculture between 1972 and 1980 followed by a sharp increase between 1980 and 1999 coincides well with the reverse trend for Clearings and Forest areas for the same time periods (Figure 4.13). As has already been discussed previously in this Chapter, until the late 1970's, agricultural areas were being abandoned or converted to other land uses in the Kullu Valley due to a lack of interest in farming which could partly explain the increase in Clearings and Forest areas until around 1980. The continued and increasing success of the horticulture industry over the past several decades prior to 1980 finally lead to rapid reconversion of Clearings and Forest lands into orchards beginning in the mid-1980s. Areas affected by natural hazard processes also appear to be sensitive to the general land use/cover fluxes dictated for the most part by economic opportunities. This is most likely due to their juxtaposition with areas that are most prone to change given their proximity to settlements, transportation corridors and flatter topography.

In terms of hazards, the most noticeable changes are the significant increase in the area of Settlements and Agriculture and the decrease in Forest cover. Singh (1989) and Sah and Mazari (1998) report that the Manali area experienced a 15-fold increase in tourist visitation from 18,500 people per year in 1971 to almost 300,000 in 1991 and according to Gardner *et al.* (2002) this figure is currently closer to 500,000. The construction of facilities and infrastructure to support the rapidly growing tourism industry in the Kullu District is seen as the primary cause of the expansion and intensification of settlements near the valley bottom and in geomorphologically sensitive areas (Gardner, 1997). According to GIS overlay results using layers showing Settlements and their proximity to the Beas River for 1972 and 1999, the general distribution of Settlements within 500 m of the river was nearly identical in both years but the actual density of Settlements and infrastructure increased by over 58%.

This increase in density seems to be the result of the intensification or expansion of existing towns and villages rather than the establishment of new settlements. Although these trends are similar to what is happening in other parts of the valley not affected by hazard processes, the fact that Settlements consistently represent the largest proportion of area affected by processes of natural denudation and that this area is increasing at an accelerated rate is most noteworthy. Alone, this trend in land use/cover change is sufficient to warrant a detailed investigation into how the consequent increase in risk and susceptibility in the area should be mitigated. However, coupling this trend with the effects of an apparent decline in Forest cover and an increase in agricultural activity represents an even stronger case for the careful examination and monitoring of natural hazards in this area. Furthermore, the expansion of agricultural and horticultural areas onto slopes affected by natural hazards not only leads to potentially lower slope stability if the fields are not maintained properly, but also can dramatically increase the level of economic and human risk (Zisheng and Luohui, 2004).

Landslides or debris flows pose a risk to individual fields as well as entire villages so the significant increase in the area of Agriculture in these hazard sites directly increases the susceptibility and risk of people and their livelihoods in the upper Kullu Valley. This apparent increase in the level of susceptibility or risk is somewhat counteracted by the noticeable decrease in Clearings particularly between 1980 and 1999 in the higher elevations. Overall however, there has been a noticeable increase in human-built structures in areas affected by landslides, rock fall, debris flow and flood activity between 1972 and 1999.

4.3 Weather and Climate and Seismic Activity

Weather, climate and seismic activity influence the location and activity of hazard processes primarily through their action as triggering mechanisms of mass wasting and flood events. The results of trend analyses over time for each of these factors are discussed below with the specific goal of evaluating their effects on the activity of erosion and denudation processes in the study area.

4.3.1 Weather and Climate

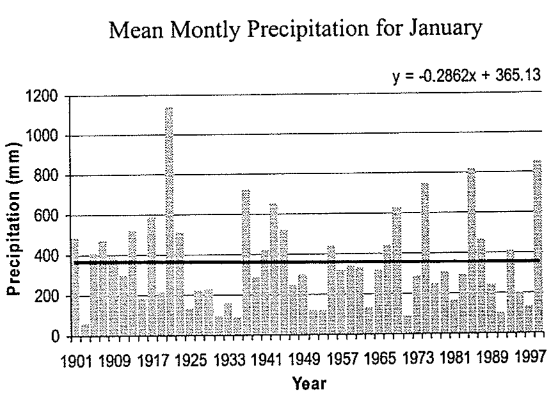
Precipitation data recorded at four meterological stations in and around the viscinity of the Kullu Valley, namely Banjar, Kullu, Naggar and Keylong (see Figure 2.1) were analyzed for changes in trends between 1901 and 1999. The selection of the 5 rainiest months (Table 4.16) agrees closely with the work of Singh and Mishra (unpublished) who analyzed a 16 year climate record and found that February, March, July and August were also associated with the highest total precipitaton and intensity and the most number of rainy days.

Table 4.16 Characteristics of the five rainiest months averaged for four climatic stations between 1901 and 1999. (India Meteorological Department, 2000)

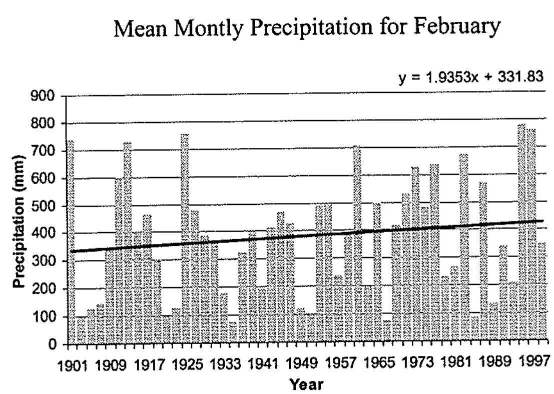
Month	Mean Precipitation	Mean Number of Days of Rain	Mean Daily Rainfall Intensity
January	358 ± 230 mm	6 ± 3	52 ± 16
February	381 ± 213 mm	7 ± 3	56 ± 20
March	469 ± 298 mm	8 ± 3	58 ± 21
July	592 ± 176 mm	11 ± 2	49 ± 9
August	600 ± 185 mm	11 ± 3	50 ± 11
Average	**480 ± 220 mm**	**8 ± 3**	**53 ± 16**

All values +/- one standard deviation

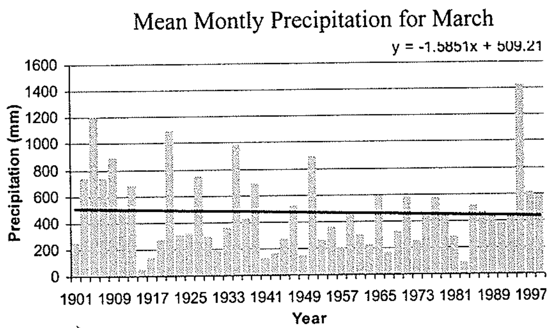
Table 4.16 above shows mean precipitation increasing steadily between January and August; the rise in July and August coincides with the onset of the summer monsoon. Variability in precipitation is relatively high as demonstrated by the high standard deviations. Although July and August have the greater number of days of rain out of the months analyzed, mean daily rainfall intensity, an important landslide triggering indicator, is highest in February and March. Figures 4.14a through 4.14o graphically show the trend in precipitation averaged for the four climatic stations along with the slope equation shown in the upper-right of each graph.



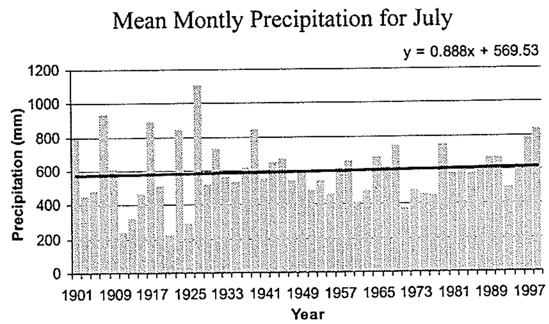
a)



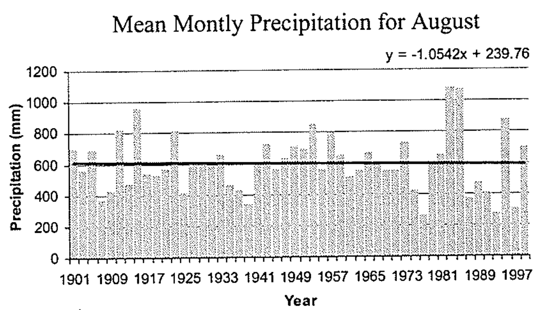
b)


Mean Montly Precipitation for March
y = -1.5851x + 509.21
Precipitation (mm)
Year

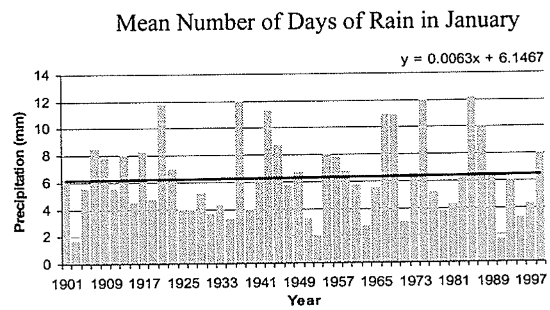
c)


Mean Montly Precipitation for July
y = 0.888x + 569.53
Precipitation (mm)
Year

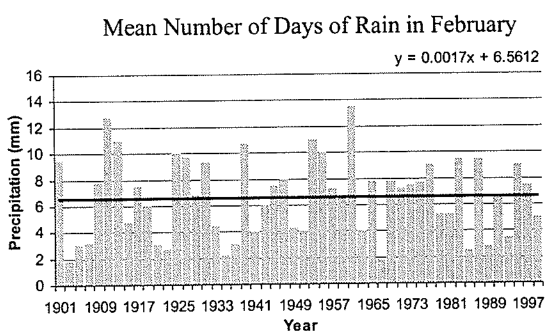
d)


Mean Montly Precipitation for August
y = -1.0542x + 239.76
Precipitation (mm)
Year

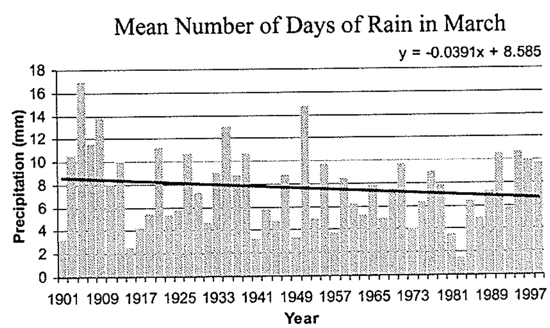
e)


Mean Number of Days of Rain in January
y = 0.0063x + 6.1467
Precipitation (mm)
Year

f)


Mean Number of Days of Rain in February
y = 0.0017x + 6.5612
Precipitation (mm)
Year

g)


Mean Number of Days of Rain in March
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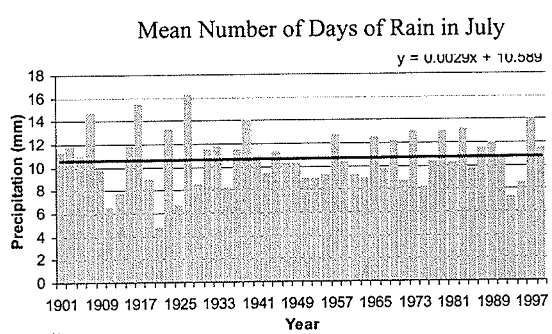
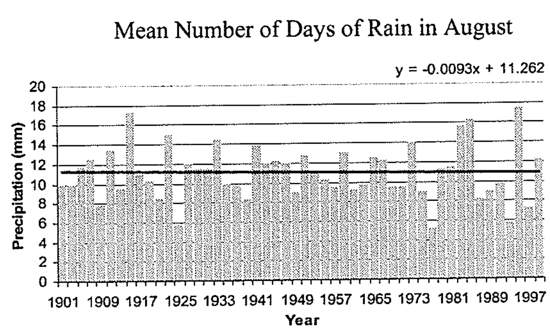
Precipitation (mm)
Year

h)


Mean Number of Days of Rain in July
y = 0.0029x + 10.589
Precipitation (mm)
Year

i)


Mean Number of Days of Rain in August
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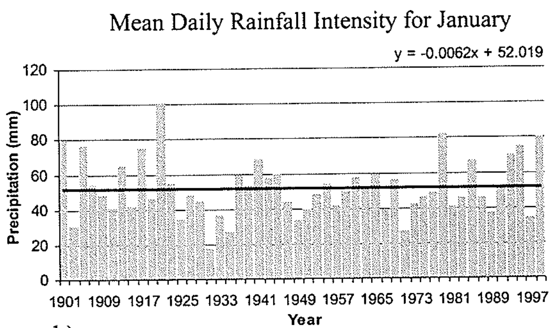
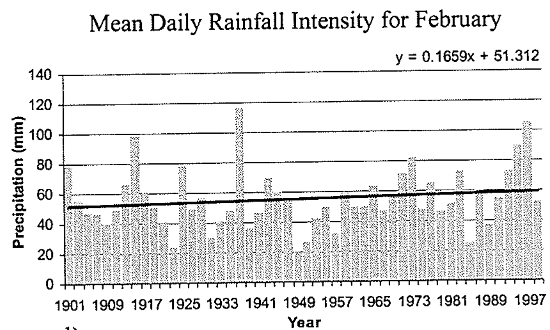
Precipitation (mm)
Year

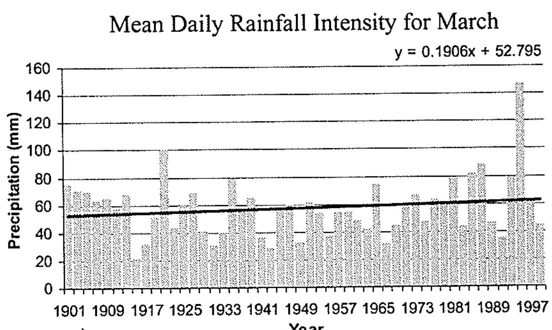
j)



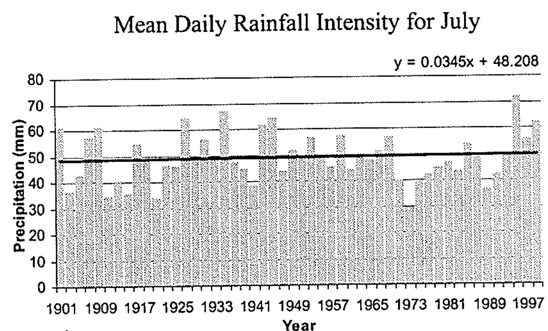
k)



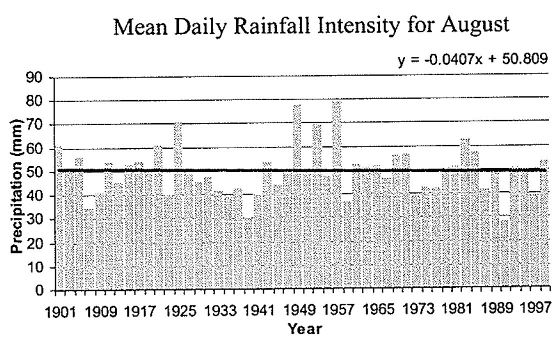
l)



m)



n)



o)

Figure 4.14 Graphs a) through e) show mean monthly precipitation, graphs f) through j) show mean number of days of rain per month and graphs k) through o) show mean daily rainfall intensity per month for all four meterological stations (Banjar, Kullu, Naggar and Keylong).

Graphs a) through e) show a very small decline in mean monthly precipitation totals for the months of March and August while for January, February and July, average monthly precipitation has increased slightly between 1901 and 1999. The average increasing trend (m = +1.411) for the months of February and July is greater than the average decreasing trend (m = -0.975) for January, March and August indicating that mean monthly precipitation in the Kullu Valley has increased by about 61 mm over the past 98 years, especially during February (increase of 190 mm over 98 years). The apparent net increase of 61 mm however, is well within the normal variability of the mean monthly precipitation (480 $\pm$ 220 mm) and consequently indicates that no significant changes in monthly precipitation have occurred in the Kully Valley over the past 98 years.

Number of days of rain per month does not appear to have changed appreciably since 1901. January, February and July show a marginal average increase in the number of days of rain of +0.004 while March and August show an average decrease of -0.024 resulting in a net average decrease of 0.7 days over 98 years. These results indicate that the number of days of rain per month has not changed appreciably considering the variability in the mean number of days of rain per month (8 $\pm$ 3).

Mean daily rainfall intensity between 1901 and 1999 is characterized by an average decline of -0.023 in the months of August and January while for February, March and July, the average trend is an increase of +0.130 indicating that the mean rainfall intensity has increased by 6.7 mm d^{-1} over 98 years. Given the mean and range of the average rainfall intensity (53 $\pm$ 16 mm d^{-1}), the computed increase of 6.7 mm d^{-1} appears to fall within the normal variability of the data, suggesting that the trend in daily rainfall intensity has not changed significantly over the past 98 years.

Monthly precipitation totals serve as an index of the volume of runoff and moisture available for entrainment of surficial material temporarily deposited on slopes or in debris flow channels. Monthly total precipitation amounts are also directly linked to the potential for flooding on the Beas River and its tributaries in the form of direct precipitation onto the channels as well as runoff supplied by overland flow, streams and groundwater. While a net increase of 61 mm in mean monthly precipitation over the past 98 years has been detected, it is unlikely that this has had any tangible effects on mass wasting and flood activity especially considering the complexity of the relationships between factors which control the thresholds of triggering mechanisms as discussed previously in this Chapter. Results indicate little change in the average number of days of rain during the five months considered. This is interpreted as having little or no significant effect on the activity of natural erosion or denudation processes operating in the area. An increase in average daily rainfall intensity was detected and although the computed value falls within one standard deviation of the mean, it represents an increase in intensity of nearly 13% over the 98 year period. The precise effects of this result on slope stability and flood activity, however, is difficult to assess due to a lack of information about minimum rainfall intensity thresholds beyond which landslides, debris flows and floods are known or likely to occur.

Temperature has a less direct impact on mass wasting and flood activity than precipitation assuming all other factors are equal. Although rapid increases in temperature can lead to the sudden melting of snow or ice causing flash flooding, debris flow and even landslide activity, this type of triggering mechanism is less common in the Kullu Valley compared with the action of precipitation or earthquakes as discussed in Section 4.3.2 below. Nevertheless, temperature directly affects biological processes which, through changes in vegetation cover and weathering processes, contribute to or detract from slope stability as well as flood magnitude and frequency. Additionally, an analysis of a monthly temperature record may reveal long term changes in temperature trends which could have long term impacts on the moisture balance in a watershed in terms of the advancement (more moist climate regime) or retreat (drier climate regime) of alpine or valley glaciers. An adequately long temperature record for the study area was not available for analysis due to Government of India security restrictions. Some authors, however, have been able to analyze various subsets of the record and some conclusions can be drawn from these results.

Singh and Mishra (unpublished) analyzed temperatures recorded at Kothi, Behang and Manali for various time periods between 1968 and 1991. Temperatures recorded by the snow and avalanche study establishment (SASE) show an overall increase in mean temperatures. Local inhabitants blame the apparent drastic climatic changes over the past 30 years on increasing deforestation, reforestation with unsuitable species and unplanned development. Climatic data recorded at Bhuntar, Kullu and Manali between 1964 and 1992 were analyzed by Singh and Roy (2002). Although the authors found no apparent change in the temperature trend, they did observe a slight increase in annual rainfall along with a slight decline in monsoon rainfall. The authors noticed an increase in the occurrence of extreme weather defined as events exceeding mean values by at least 2 standard deviations and state that even small changes in local weather can have noticeable effects on soil erosion, landslide activity and flash flooding. Resident farmers polled by the researchers perceive that there has been a decrease in total rainfall and an increase in snowfall, hail storms and the frequency of wind gusts. According to research carried out by Sah and Mazari (1998), temperatures in the Kullu Valley have increased during the past century resulting in increased rates of glacial melt and thus runoff.

4.3.2 Earthquakes

Following precipitation, earthquakes are considered the second-most influential triggering mechanism of slope failures in the Kullu Valley according to Rao (1997). The vertical and horizontal ground accelerations during earthquake activity have the potential to rapidly alter the balance between resisting and driving forces within a slope. The Kullu Valley is situated in earthquake hazard zone V (the highest) and has been subjected to ground accelerations ranging from 0.16g to 0.40g (http://www.asc-india.org/seismic/hp.htm, 2004). An increase in either the magnitude or frequency of earthquakes can potentially increase mass wasting activity by triggering either more or larger slope failures. An earthquake record with information about the location, date and magnitude for each event recorded can be used to determine how the frequency and magnitude of earthquakes has changed over a period of time.

Data on earthquake events in proximity to the study area were collected from records compiled by the USGS between 1882 and 2004. The record consists of 1541 earthquakes with information on the year, month, day and time of the earthquake along with the latitude, longitude and magnitude of each event. Figure 4.15 shows the linear regression relationship between magnitude and date indicating that while the frequency of earthquakes appears to have increased substantially, the magnitude of individual earthquakes has decreased according to the negative slope of the trend line (m = -0.022).

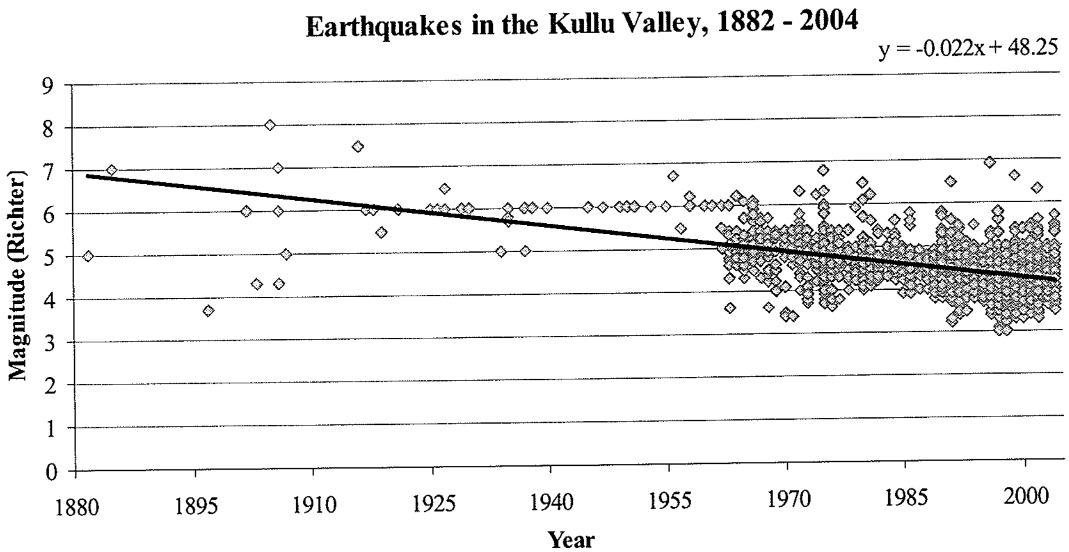


Figure 4.15 USGS earthquake data showing 1541 events in the vicinity of Kullu Valley between 1882 and 2004. (USGS, 2005)

Figure 4.15 indicates a distinct increase in earthquake frequency just after 1960 which, corresponds to the proliferation of more accurate and sensitive observatories and recording stations starting in 1963. As discussed in Section 2.1.2, the continued modernization of seismic stations capable of detecting lower magnitude earthquakes, may lead to the false assumption that earthquake frequency has increased while earthquake magnitude has decreased.

Results from a two-sample unequal variance t-test show that the pre-1963 and post-1963 earthquake populations are statistically different based on magnitude (*t-Stat* = 14.078, *t-Crit* = 2.005 with $df = 54$ and $P = 1.025 \times 10^{-19}$ at $\alpha = 0.05$). Mean magnitude for the pre-1963 population is 5.9 while for the post-1963 population the mean is 4.5. Thus all subsequent earthquake activity was analyzed using data between 1963 and 2004.

Figure 4.16 below shows the date of all earthquakes between 1963 and 2004 plotted against magnitude on the Richter scale. The trend (m = -6.0 x 10^{-5}) indicates the rate of change per day instead of per year which results in a net decrease in Magnitude of 1.0 over 45 years, which is identical to the trend derived using the 1882 to 2004 dataset. Based on the median date of 1983, average earthquake magnitude for pre-1983 earthquakes (M = 4.9) differs significantly from post-1983 earthquakes (M = 4.3) based on the results of an unequal variance t-test (*t-Stat* = 18.902, *t-Crit* = 1.962 with df = 1026 and P = 1.321x10^{-68} at α = 0.05). This indicates that even after the main effects of differences in number of observatories and their sensitivity are minimized earthquake magnitude appears to have decreased while frequency has increased from 513 events pre-1983 to 974 events post-1983 over the same 20.5 year time period.

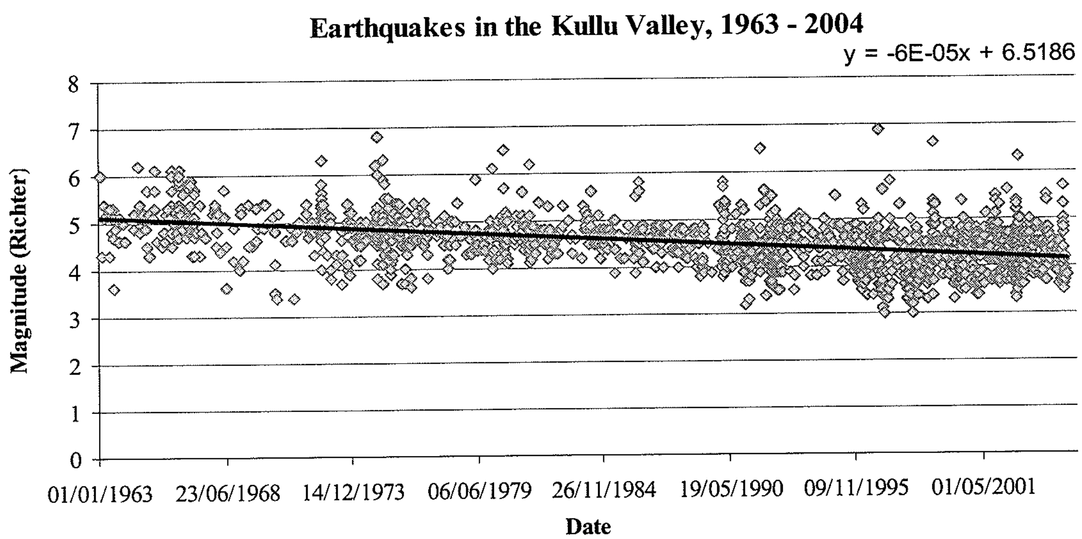


Figure 4.16 USGS earthquake data showing 1487 events in the vicinity of Kullu Valley between 1963 and 2004. (USGS, 2005)

Kayal (2001) demonstrated that the number of earthquakes generally increases 10-fold with each decrease in magnitude of 1.0. However, this is not the case here as the frequency of earthquakes appears to only have increased by a factor of 2.4 extrapolated from the decrease in magnitude of 0.6 between pre- and post-1983 events.

The precise effects of the significant decrease in earthquake magnitude coupled with the apparent increase in their frequency on mass wasting and denudation activity in the Kullu Valley are difficult to interpret. It is possible that more lower magnitude earthquakes that are below the threshold required to initiate landslides and rock falls are occurring now than before. This would potentially translate into a decrease in the activity of hazard processes and a corresponding increase in slope stability. Conversely, if earthquake magnitude has remained sufficiently high to trigger various mass wasting processes and this is coupled with the significant increase in their frequency, then it is possible that slope stability has declined over the past 41 years due to the occurrence of more earthquakes that are capable of triggering slope failures which can then cause damage and destruction of lives and property.

4.4 Sources of Error

The identification of hazard sites in the field through the interpretation of geomorphological evidence introduced a relatively low level of error due to having carried out the site investigations during the monsoon when mass wasting and flooding activity is known to be highest. The 30 m pixel resolution DEM generated from 1:100,000 scale maps with 40 m contour intervals and its associated first- and second-order derivatives introduced a level of uncertainty into some of the model results and output data, namely the DEM, slope, and aspect layers, which served as primary inputs into the friction models used to generate deposition, inundation and bank erosion layers in the GIS. According to Gao (1997), the root-mean squared error (RMSE) of a DEM can be estimated using the equation

$$RMSE = \frac{(7.274 + 1.666S)D}{1000} \qquad (10)$$

where S is resolution expressed in km and D is contour density expressed as km km^{-2}.

Given the 30 m pixel resolution and average contour density of 100 km km^{-2}, the RMSE for the DEM used in this analysis is 0.73, which is sufficiently high to warrant its use for this type of analysis. However, the relatively small scale and coarse contour interval of the original topographic maps meant that many larger-scale topographic variations and terrain details were obscured in the resulting DEM and its derivatives (Holmes *et al.*, 2000). The elevation, slope angle and slope aspect values measured in the field using an altimeter and GPS, inclinometer and compass, respectively were found to be statistically indistinguishable from those measured in the GIS layers for the same locations (Mantovani *et al.*, 1996). The modeled landslide and debris flow deposition areas also closely matched those surveyed in the field in areal extent and distribution. However, larger-scale maps with a finer contour interval and better spread algorithm such as the elliptical approach proposed by Xu and Lathrop Jr. (1995) would have resulted in a more precise representation of the terrain and deposition sites. The flood model in particular requires a much finer contour interval, ideally sub-meter, in order to accurately predict areas susceptible to inundation. GIS results from the flood model based on the available DEM represent only a generalized distribution of areas that may be prone to inundation and cannot be used for precise flood monitoring or control. In fact, as already discussed in Section 3.6.5, the hydraulic equations employed in the model were valid for confined sections of the river only, which were estimated to comprise approximately 50% of the length of the Beas. This restriction can be eliminated given better topographic input maps without significantly changing the model parameters.

It is important to recognize that any hazard evaluation involves a high degree of uncertainty that depends on researcher experience, aim of study, study area characteristics, the age and type of mass movements, the scale type and quality of the spatial data sources (e.g. satellite images, maps or air photos), and the processing required to convert analog data to digital form for use in a GIS (Mantovani *et al.*, 1996). Generation of the three land use/cover maps involved a number of disparate data sources. Decisions regarding which input layers to include in the analysis and which algorithm to perform the supervised classification with were aimed at reducing redundancy and maximizing accuracy. Consequently, it was necessary to run multiple iterations of the classification using different input data and classification algorithm combinations in order to determine the statistical variance of the results. This type of sensitivity analysis allowed for the identification of a factor or combination of factors that were least correlated and led to an assessment of the statistical differences between land use/cover change results for the entire study area as well as for just the areas affected by erosion and inundation processes. Input layers used in the analysis included all spectral bands, band ratios, vegetation indices and ground validation layers for each of the three LandSat scenes, DEM, slope and aspect layers as well as the GIS layers showing release and modeled deposition sites for landslides, debris flow, rock fall, flooding and bank erosion. The factors modified between iterations included using different band ratios and vegetation indices, changing the spectral resampling technique and using raw training values with equal prior probabilities, edited training values with equal prior probabilities and edited training values with individual prior probabilities.

Sensitivity analysis results indicate that the output land use/cover maps were most sensitive to whether the training data used in the supervised classification were "raw" values with equal prior probabilities or if they had been edited to minimize within-class variance, maximize between class variance and incorporated prior probabilities. More importantly, it was found that there were no statistical differences in the results of the land use/cover change analysis for either the entire study area or the areas affected by hazard processes among the several dozen classification iterations generated. Although the distribution and pattern of land use/covers different somewhat between the various output layers created, the differences were statistically insignificant and did not affect the final overlay results.

Chapter 5 – Conclusions

5.0 Introduction

In many ways, mountains represent the ultimate paradoxical landscape. They are the source of tremendous natural resources including water, forests, fertile soil, and minerals, while at the same time they are regarded as inhospitable and relegated to the margins of the habitable world. Mountains may appear as impenetrable and indestructible fortresses of refuge and remoteness when viewed from afar, yet up close their fragility and sensitivity to the complex effects of weathering processes, seismic activity and even human disturbance are just now beginning to be understood. On-going changes in land use/cover brought about primarily by mounting anthropogenic pressures in many mountain regions have heightened the concern regarding the resilience of these landscapes and associated ecosystems.

The exposure and susceptibility of people and their livelihoods to risks posed by natural processes of erosion and denudation are not static, rather they respond to changes in such factors as precipitation, temperature, seismic activity as well as human activity expressed through land use/cover. The exact responses in susceptibility and risk caused by changes in these factors are complex and still poorly understood. The need to improve our understanding of how climate, seismic activity, and changes in land use/cover affect the activity of natural erosion processes is driven by an increased awareness of human-induced climate change, the continued expansion and intensification of human infrastructure into mountain areas and the need to systematically collect information in order to make sound decisions regarding the distribution of financial resources and the development of equitable policy in mountain areas.

5.1 Purpose and Objectives

Has the exposure of people, their livelihoods and associated infrastructure to natural processes of erosion and denudation changed over the past several decades along the main transportation corridors in the Kullu Valley? This is the general question addressed in this thesis. It is hypothesized that the recent and ongoing expansion and intensification of urban infrastructure is increasing the susceptibility and thus risk of people and property to natural hazards posed by processes of denudation and flooding along the main network of roads adjacent to the Beas River in the Kullu Valley. The specific objectives are to;

1) Identify, locate, document, map and model sites of known and potential slope instability and inundation adjacent to the main network of roads along the Beas River.
2) Identify the pattern of land use/cover change for areas in close proximity to the Beas River and for sites affected by erosion and flooding processes between 1972 and 1999.
3) Estimate how changes in land use/cover, climatic factors and seismic activity have altered the susceptibility of people and infrastructure to natural hazards in the Kullu Valley.

5.1.1 Objective 1 Results

In total, over one hundred sites of active and suspected slope instability, inundation and bank erosion were identified along the main transportation routes in the study area based on geomorphological field surveys conducted in 1999 and 2000. This total is comprised of 61 landslides, 10 rock fall sites, 23 debris flow channels and numerous sites of inundation and bank erosion. The overall distribution and location of hazard sites defined as areas prone to mass wasting and denudation in close proximity to the Beas River agrees well with the results of other researchers (e.g. Gardner, 2002; SASE, 2000; Sah and Mazari, 1998; Gardner *et al.*, 1997; Tolia *et al.*, 1997).

Data for release, deposition and inundation areas collected in the field and extracted from factor layers served as the main input into a GIS database. Maps of the release, deposition and inundation sites were linked to their attributes to create a GIS-based hazards database. This fulfills the first objective of creating a comprehensive GIS-based map and inventory of natural hazard sites along the main transportation network in the Kullu Valley. Creation of these map and database products within a GIS framework affords a high level of flexibility and scalability, allowing new sites, attributes, or factor layers to be added or edited efficiently without changing the database structure. This is an important consideration given the changing nature of the data being analyzed and the requirement to update it on a regular basis (e.g. every year) (Zhou *et al.*, 2002).

The inventory map and database show important causative factors (e.g. slope parameters and land use/cover) about the pre-failure conditions (i.e. 1972 and 1980) of landslides, debris flows, and rock falls (see Section 3.6). There is also strong potential for the map and database to be used in a planning and decision-making capacity by local planning authorities and other stakeholders in order to reduce the potential for future negative interactions between people, their livelihoods and natural processes of erosion and denudation.

5.1.2 Objective 2 Results

Land use/cover change was analyzed using a pair-wise comparison of the land use/cover maps for three different time periods for the whole study area, the release and deposition zones (where applicable) for each hazard type as well as all deposition and inundation areas combined. The historical land use/cover map generated using a 3-D viewshed analysis incorporating current and historical ground-based photographs and a DEM, was excluded from analysis due to an unacceptably low area of coverage which significantly hampered statistical analysis and the interpretation of results.

The total change in percent area of each land use/cover category and the factor by which each category increased or decreased between 1972 and 1999 was determined. Land use/cover change between 1972 and 1999 for the whole study area is characterized by net losses of Forest (-7.0%) and Agriculture (-0.9%) and by a net increase in Clearings (+4.6%) and Settlements (+3.3%). Examining the factor by which each land use/cover category has changed reveals that Settlements and Clearings have increased in area by a factor of nearly 1.5 and 1.2, respectively. Forest has declined by a factor of 0.9 and Agriculture area has remained fairly constant with a factor of change of less than 1.04 over a period of 27 years. The expansion of infrastructure is significant because many of the new settlements and access roads constructed since 1972 have been built near the valley bottom in close proximity to existing sites of flooding or slope instability. An examination of land use/cover change between 1972 and 1999 in areas affected by flooding and slope instability reveals that Settlements have expanded substantially (by a factor of over 1.5) into areas of known or suspected hazard. In summary, there has been an increase in the exposure of people, buildings and transportation routes to the existing processes of mass wasting and flooding between 1972 and 1999. These conclusions agree closely with those of Gardner *et al.* (2002, 1997), Sah and Mazari (1998), Toila *et al.* (1997), and Singh and Pandey (1996).

The net loss of Forest and Agricultural land, coupled with an increase in Clearings, has potentially altered the actual activity of mass wasting and flooding processes. As documented in the literature, the clearing of forests or conversion to agricultural fields can lead to increasd runoff, sheet erosion, slope instability, and denudation (Gerrard and Gardner, 2002; Barnard *et al.*, 2001; Blaschke *et al.*, 2000; Marston *et al.*, 1998; Sarkar *et al.*, 1995; and many others). Results show that Forest was most frequently converted to Clearings and Agriculture and Agriculture was most often converted to Clearings between 1972 and 1999 on slopes with characteristics similar to those of known landslide and rock fall release sites in the study area. Although other factors need be considered in order to unequivocally conclude that these land use/cover changes have materially increased the spatial and temporal frequency of hazardous processes, land use/cover change is considered one of the main factors capable of rapidly altering some of the preparatory and triggering factors that govern slope stability and inundation (García-Ruiz and Valero-Garcés, 1998).

The consequences of these changes can further be explored by assessing how land use/cover has changed specifically in landslide and rock fall release areas and adjacent slopes. The most prevalent changes in landslide and rock fall release areas between 1972 and 1999 are a significant increase in Agriculture (factors of 1.7 and 2.4, respectively), a noticeable decrease in Forest (factors of 0.5 and 0.3, respectively), and a decrease in Clearings (factors of 0.7 and 0.9, respectively). Land use/cover changes on slopes in close proximity (i.e. <500 m) to landslide and rock fall release areas over the same time period are characterized by an increase in Clearings (factors of 1.3 and 1.2, respectively) and Settlements (factors of 1.4 and 1.1, respectively) and a decrease in Forest (factors of 0.7 and 0.8, respectively).

Perhaps changes in land use/cover over the past 27 years have sufficiently altered the preparatory factors affecting sites of recent instability identified in the field, causing them to fail under normal monsoonal conditions. Numerous authors have identified similar patterns of land use/cover change in various regions throughout the Himalaya (e.g. Saha *et al.*, 2002; Zurick and Karan, 1999; Rowbotham and Dudycha, 1998; Singh and Pandey, 1996; Rawat and Rawat, 1994), indicating that the changes affecting the Kullu Valley are not unique to this particular area, rather they represent the general trend prevalent in this mountain region.

5.1.3 Objective 3 Results

In the Kullu Valley, the expansion and intensification of settlements into geomorphologically active sites is the main reason for the increase in the susceptibility and risk of people, property and livelihoods to slope erosion and flooding processes (Gardner *et al.*, 2002; Collison *et al.*, 2000). The increase in infrastructure between 1972 and 1999 in parts of the Kullu Valley that are most frequently affected by deposition and flooding processes, exposes more people to natural and human-induced erosion processes (Singh and Roy, 2002; Blaschke *et al.*, 2000; Sah and Mazari, 1998). Changes in land use/cover, specifically the replacement of mature forest stands with clearings or agriculture fields may have also materially altered the magnitude and frequency of mass wasting processes. However, without access to a detailed history of activity for specific sites, the only conclusion that can be drawn is that the observed changes in land use/cover in release areas may have altered some of the predisposing factors directly affecting slope stability in the Kullu Valley. Land use/cover changes which have potentially altered slope stability in one region may also lead to similar changes in stability in other regions. The precise effects on individual slopes varies due to differences in lithology, geomorphology, type of surficial material, vegetation cover, climate and weather and many other factors (Schweik *et al.*, 1997).

The cumulative effects of climate on the activity of landslide, debris flow, rock fall and flooding processes in the study area were assessed based on a 98-year precipitation record and the results of several previously analyzed temperature datasets. Precipitation in general and rainfall intensity in particular are regarded as common triggering mechanisms of slope failures and floods (Mason and Rosenbaum, 2002; Toila *et al.*, 1997; Tianchi, 1994; Bloom, 1990; Caine, 1980; and others). The results of an analysis of mean monthly precipitation, number of days of rain per month and mean daily rainfall intensity (Figure 4.14) indicate that there has been little no change in the frequency and/or magnitude of atmospheric events that would potentially trigger hazardous processes proximal to the main transportation routes. Although small variations were detected in each of the three indicators listed above for the five rainiest months, they are well within the natural variability of the datasets so it is unlikely that precipitation trends have changed appreciably over the past 98 years in the Kullu Valley. There is, however, little direct evidence in the form of frequency of occurrence data for any of the hazard processes investigated from which to draw firm conclusions. The impacts of climate change on erosion and flooding processes are less immediate than those resulting from land use/cover change or short-term weather events and more difficult to predict accurately.

The results of an analysis of previously published temperature records results are also inconclusive. The general consensus amongst researchers is that the Kullu Valley is experiencing a warming trend (Sah and Mazari, 1998). Consequently, recession of the colder climatic belt to higher altitudes over the past 100 years and the melting of glaciers which results in additional runoff may have resulted in a more humid climate regime in the Kully Valley. This is supported to a degree by results from the precipitation record analysis. The impacts of these results on the activity of mass wasting and flood processes, however, are difficult to assess. Precipitiation is regarded by many researchers as the primary triggering mechanism of various mass wasting processes (e.g. Barnard *et al.,* 2001; Ellen and Mark, 1993) and directly controls flooding and bank erosion (Brooks *et al.*, 1997). Results of this research suggest that the minor changes in precipitation and temperature are unlikely to have altered the activity of erosion processes in the Kullu Valley over the past century.

Results from the analysis of a record of earthquake activity show that between 1963 and 2004, average earthquake magnitude decreased by 0.6 *M* from 4.9 to 4.3 while the number of events nearly doubled from 513 before 1983 (the median date) to 974 after 1983. Although the earthquake record dated back to 1882, it was found that the proliferation and modernization of seismic recording stations in and around the study area starting around 1960 introduced a significant bias into the results, thus only events since 1963 were analyzed.

The trend indicates that there are now more earthquakes of lower magnitude occurring in the Kully Valley. However, this is at least partially a result of the installation of more seismic recording stations with higher sensitivty. Earthquakes have triggered landslides, debris flows and rock falls in the past, and will continue do so in the future, although it is difficult to accurately predict how these changes in earthquake frequency and magnitude have affected their role as triggering mechanisms (Barnard *et al.*, 2001; Chaudhury, 1995; Bloom, 1990). Nine major earthquakes ($M < 6.0$) have been recorded in close proximity to the Kullu Valley since the 7.8 Magnitude earthquake in Kangra in 1905 and most of them have triggered at least minor mass wasting activity. However, according to Bilham (2004), northern India is overdue for a large ($M < 8.0$) earthquake based on an in-depth analysis of available earthquake records dating back two millennia (Figure 4.17).

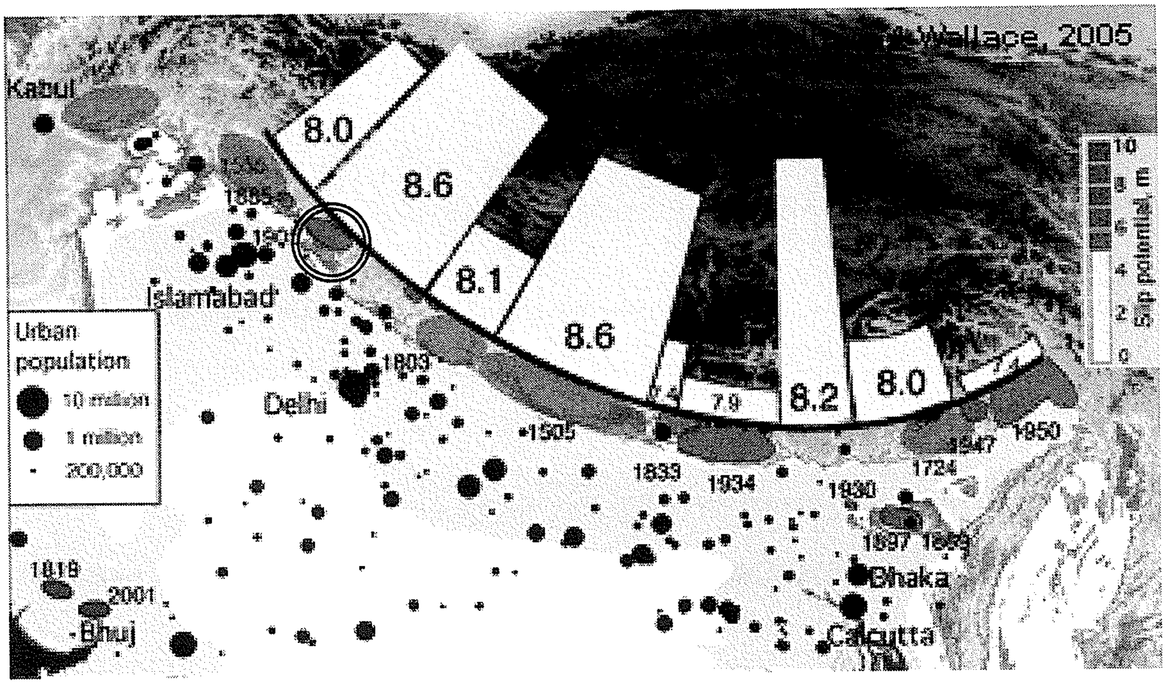


Figure 4.17 Predicted Magnitudes and slip potential along the Himalayan arc. Circle indicates approximate location of study area. (Bilham and Wallace, 2005)

It is unclear whether the detected decrease in earthquake magnitude is significant enough to reduce the magnitude below the threshold required to cause sufficient ground accelerations to initiate slope failures. It is also unknown if the apparent increase in earthquake frequency will result in more slope failures. Furthermore, will the higher predicted frequency compensate for the apparent decrease in magnitude? There have been no studies in the Kullu Valley attempting to link earthquake frequency and/or magnitude to slope failure activity and, therefore, no valid conclusions can be drawn regarding what effects these changes in earthquake magnitude and frequency have had on the activity of mass wasting processes over the past 21 years in the Kullu Valley.

5.2 Implications of Conclusions

Investigation of the factors that characterize and influence the location and activity of mass wasting and flood events is important because these are the dominant processes that are reshaping the present-day Himalayan landscape. Several authors have recognized these factors as the main forces controlling hill slope evolution in the Himalaya and other mountain environments (Shroder Jr., 1998; Carson, 1985 *in* Vuichard, 1986). The mapping and modeling techniques developed and used here and the results derived through their application to the analysis of hazards in the Kullu Valley, close several knowledge gaps identified in the literature review (see p. 5-6). An overriding one is the need for a more systematic approach to hazards-related data collection and analysis. This has been addressed through the development of the globally-applicable GIS database and hazards mapping system (Zurick and Karan, 1999; Gupta, 1997; Ives and Messerli, 1989). The GIS hazards database is capable of accepting a wide variety of hazards-related data sources, depending on the availability of information at a specific location, and using those data to estimate areas that are or may become subject to mass wasting and flooding activity. Further verification of model performance is required as discussed below, but basic operational parameters have been established and the system can be applied to other areas in the Himalaya in order to acquire more data on the activity of natural hazards and their effects on people and infrastructure (Hofer, 1993; Metz, 1991; Hamilton, 1987; Byers, 1986; Ramsay, 1986; Carson, 1985).

It has also been established that over relatively short periods of time (e.g. <50 years), land use/cover change is capable of altering some of the main preparatory factors governing slope stability and flood activity as well as the susceptibility and risk in an area. Few other studies have recognized the importance of the potential effects of land use/cover change on hazards (see p. 61). More research is required in order to better understand the relationships between land use/cover change and the activity of mass wasting and flooding processes.

Hazard inventory and susceptibility maps are important inputs into a comprehensive zoning plan and provide crucial information on the spatial distribution of possible sites of erosion and flooding (Abrol, 2001). The application and enforcement of a zoning plan that takes into consideration the inherent natural processes operating in the valley and identifies areas where non-vital development should be limited or restricted may greatly reduce risk by minimizing the exposure of people and property to mass wasting and flood activity (Blaschke *et al.*, 2000). A comprehensive overview of the location and distribution of hazards sites provides the local government and various stakeholders with a strong foundation for the reexamination of the land management policy and plan currently in place in the Kullu Valley. This type of information could be the catalyst for the allocation of funds for the maintenance of potentially unstable slopes and the mitigation of hazards in areas deemed to be highly vulnerable to risk from landslides, rock falls, debris flows or flooding. Although the original inhabitants of the Valley seemed to have a strong sense of the inherent dangers associated with living in an active mountain environment, the growing visitation and inhabitation of the Valley by people from the plains and beyond raises a need for the reeducation of the public about the consequences of not respecting the ever-changing and dynamic nature of the surrounding physical environment.

This study has also exposed an apparent lack of focus in the discipline of geomorphology on how land use/cover changes specifically in deposition areas affect susceptibility and risk of mountain people, their livelihoods and associated infrastructure (see p. 5-6). Despite the range of effective techniques used to recognize and identify areas of probable slope instability or flooding, both through ground surveys and remote sensing means, there has been little discussion about the merits of separately analyzing the release and deposition areas (with the exception of Donati and Turrini, 2002). This is partly a function of the potential difficulties associated with modeling or predicting runout zones but may also be due to an apparent lack of need to separate a hazard site into the two distinctly different components of release area and deposition zone. The importance of this separation is emphasized here because it allows for a separation of the factors that influence risk posed by a site to the people and structures down slope. This is especially critical in the context of a historical examination of changes in susceptibility or risk because, as discussed above (p. 215-216), land use/cover change in deposition areas is the single most influential factor capable of immediately altering the hazardousness of a place.

Changes in land use/cover over time have demonstrably altered the exposure of people to natural hazard-related disasters in the Kullu Valley. Changes in the trends of physical triggering mechanisms including precipitation, temperature and earthquake activity were also evaluated. The influence of these factors on the exposure of people to natural hazards and the associated risks, however, is less certain and requires further investigation.

5.3 Limitations

5.3.1 Time-related Limitations

This study of mass wasting phenomena in the Himalaya suffers from the same general problems plaguing most other research efforts of this type, namely the limited time of study (Flageollet, 1996) and geographical scope of the study area. These limitations make it difficult to take the results derived from one Himalayan valley and apply them to another owing to the high heterogeneity of the physical and cultural composition characterizing this and other mountain regions. Nevertheless, the value of such research lies not only in its direct application to other areas, but also its contribution to the overall body of knowledge relating to the study of mountain hazards and the advancement of hazard-related techniques. The techniques developed here represent a synthetic approach to the detection and analysis of mountain hazards anywhere on earth thus they constitute an adaptive and efficient GIS-based method of assessing the current and historical state of natural hazards in an area.

The results of this study serve as baseline data for use in future investigations of slope stability and flooding in the Kullu Valley and in other similar environments. A comprehensive characterization of the state of natural hazards for a particular time is an important element in determining how various influential factors have changed over time and more importantly, how the exposure and risk of people and infrastructure has been affected by these changes. Incorporation of the historical 1920 land use/cover map, which would have significantly improved interpretation of how risk has changed over a span of almost 80 years in the study area, was not possible due to the limitations discussed previously (see p. 172)

5.3.2 Data Limitations

One of the potential drawbacks of these methods is the requirement for accurate remote sensing imagery and GIS layers, the availability of which is highly variable depending on where the methods are applied. In the case of this research, several crucial data sources were unavailable including a reliable road map, aerial photographs, large scale topographic and floodplain maps and, a geological map. These lack of data degraded the efficiency of the applied techniques and the reliability of results. However, at the same time, they provided an opportunity to evaluate alternate methods including generation of a road map using GPS equipment, the identification and location of hazard sites through geomorphological interpretation of slopes, and identification and extraction of a drainage network from LandSat imagery. Although the available topographic maps were of sufficient scale to generate functional friction and inundation models for the slope processes and Beas River, respectively, larger scale maps with more detail would have afforded a higher level of sensitivity in terms of more accurately predicting run-out and inundation zones.

These types of models and techniques will certainly benefit from the proliferation of more detailed satellite imagery in terms of providing researchers with more frequent coverage of areas of interest with higher spatial, spectral and radiometric resolutions. Higher resolution imagery allows for better discrimination between land use/cover categories and easier recognition of features of interest, including individual structures, debris flow channels and landslide scars. The ability to better distinguish between different crop, vegetation and rock types, field construction techniques, and urban densities would further increase our understanding of the relationships between these factors and the activity of mass wasting and flood processes. However, the problems posed by cloud cover, topographic shadows and scene calibration requirements of multi-temporal data are still present. The continued refinement of radar-based remotely sensed imagery may eventually overcome these limitations.

Creation of the historical map of land use/cover demonstrated the utility of historical data including terrestrial photographs and indigenous knowledge in risk assessment. Although data limitations, namely the limited areal coverage afforded by the historical photos, seriously restricted the usefulness of the historical map, the methods employed here provide a sound basis for the extension of risk assessment and land use/cover change analysis beyond the limitations posed by availability of remote sensing data.

5.4 Implications for Further Research

Throughout the course of this research, several opportunities for further study were identified. Some of these opportunities were borne out of the limitations encountered while others are more closely associated with the synthetic and globally-applicable nature of the methods and techniques developed and applied here.

There is a strong need to further validate the accuracy and reliability of the runout and inundation models. The effects of incorporating more detailed representations of the terrain in digital format on the ability of the models to predict runout and inundation zones with better accuracy can only be gauged if abundant data on the dimensions and spatial patterns of previous runout and inundation zones is available. The need to better delineate zones of potential deposition and flooding is directly linked to the association of these areas with flatter slopes and lower relief which renders them attractive for the expansion of settlements and other infrastructure. Future studies of mountain hazards should strive to separately analyze release and deposition areas of various slope processes including landslides, flows and falls as the driving forces acting on these two components of a hazard site manifest themselves in unique ways.

The application of these techniques to mountain areas in other parts of the world would be necessary in order to validate their performance and confirm their intended globally-applicable nature. The high level of consistency afforded by these techniques promotes less biased comparisons of results from disparate study areas and addresses one of the main problems plaguing natural hazards research not only in the Himalaya in particular but other mountain regions as well. The relative simplicity of the methods renders them easily transferable to other regions. This is an important factor in the collection of systematic and accurate data on hazards throughout the Himalaya and other mountain regions beyond. It is important to establish benchmark data characterizing the current state of natural hazards in individual valleys in order to determine future changes in the activity of erosion and denudation processes and the risk they pose to people and settlements.

Given the availability of high spatial resolution satellite imagery, the resulting inventory map showing modeled deposition zones, can be used to predict the scope of the required landslide clearance operation. This is based on a relationship between landslide frequency and magnitude which relies only on the width of the release scar to arrive at an accurate volume estimate as per the model developed by Haigh (1984). Calibration of the model with empirical data including rock type, climate, and age of road would be required to account for site-specific differences. Future areas of slope instability in the Kullu Valley and elsewhere can be predicted by using the derived parameters characterizing known hazard sites and applying them to a multivariate statistical analysis in order to find other areas with a similar combination of influential parameters (Carrara *et al.*, 1991, 1990; Bernknopf *et al.*, 1988; Carrara, 1988).

The final implications of this research go beyond the field of study of geomorphology and physical geography and into the realm of land management, policy development and socio-economic analysis. The ultimate intended application of the results is to utilize the hazards inventory map in a comprehensive analysis of risk and susceptibility as part of a holistic land management plan for the Kullu Valley. The inclusion and subsequent enforcement of the land management plan and policy go far beyond the scope of this research yet this in fact represents the ultimate application of the presented results. Although the application of individual models and techniques to other mountain regions as discussed above is an important step toward their validation, the ultimate test of the methods developed and described here would require their implementation into a management plan which would result in a tangible reduction in the destruction of property, lives and livelihoods in the area of interest. The GIS hazards inventory and map represents a comprehensive assessment of the current and historical state of natural hazards in the Kullu Valley and has the potential to reduce susceptibility and risk to people and property from natural erosion and denudation processes.

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