Landslide risk assessment along a major road corridor based on historical landslide inventory and traffic analysis

Jagannath Nayak

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by

Jagannath Nayak

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Thesis Assessment Board

Chairman	Prof. Dr. Victor Jetten (ITC)
External Examiner	Dr. D.D. Joshi (SDMC, New Dehli)
Supervisor	Mr. I.C. Das (IIRS)
IIRS Member	Dr. P.K. Chamapatiray (IIRS)
ITC Member	Drs. Michael Damen (ITC)

Thesis Supervisors

Dr. Cees van Westen (ITC)
Mr. I.C. Das (IIRS)

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Abstract

Landslides are destructive and annually recurring phenomena which cause disruption of traffic and fatalities along the road in the Himalayas. They are more frequent along the cut slopes of the transportation routes such as road corridors than on natural slopes. Risk quantification of landslide is one of the major challenges in research because of the uncertainty associated with its occurrence. This study aims at quantifying the amount of direct risk for a part of National Highway 108 (Uttarakhand), based on the different types of vehicles and different landslide types, magnitudes and expected return periods and the indirect risk generated as the loss of profit due to the blockage of the National Highway 108 by landslides. A multi-temporal inventory of landslides was prepared with the help of available BRO records from 1994 to 2008 and using 12 multi-spectral and panchromatic images of IRS and Cartosat. On the basis of field data and signatures obtained from satellite images, 178 landslide events were identified and separated into rock and debris slide with 3 magnitude classes for each landslide type. In total 164 mapping units were generated for the study area for the characterization of landslides. For these 18 hazard scenarios were developed on the basis of 2 landslide types, 3 magnitude classes and for 1, 3 and 5year return periods. For each of these scenarios a Poisson probability model was used for estimating the temporal probability and direct spatial probability was estimated from the area of the landslide with respect to the area of the mapping unit. High hazard for rock slide magnitude III and debris slide magnitude III was obtained as 0.69 and 0.77 respectively in a 5yr return period. The lowest hazard was estimated for debris slides with a magnitude I showing 0.002 probability of hazard. The vulnerability of different vehicles was estimated on the basis of Average Vehicle Density for particular type of vehicle and different magnitudes of landslides with the help of a Poisson Curve. Highest vulnerability of two wheelers, four wheelers and large vehicles was obtained as 0.8, 0.6 and 0.4 respectively for rock slides with a magnitude III. The vulnerability of the road itself was estimated on the basis of the length of the road damaged due to a particular landslide, taking into account slide material accumulation, removing cost and repairing cost of the damage road. Rock slides with magnitude III show the highest vulnerability for road i.e. 0.9. Specific risk to different elements at risk was calculated on the basis of the 18 hazard scenarios for two wheelers, four wheelers, big vehicles and the road itself study with the help of collateral data obtained from the field. Direct risk for different vehicles due to all magnitudes of debris slide was found to be 70000 $ while direct risk for different vehicles due to all magnitudes of rock slide 245000 $. Direct risk of road was found to be 2200000 $ due to rock slide which was quite higher than the direct risk of road due to debris slides i.e.540000 $. Indirect risk in this study was calculated on the basis of road blockage time and loss of profit to various business types in Gangnani, Harsil and Sukhi Top during peak season. The highest indirect risk was observed in religious vendors for both the places i.e.9000 $ in Gangnani and 130000 $ in Harsil and Sukhi Top. This study in a Himalayan road corridor serves as a case example for the assessment of quantitative risk for landslides which can be useful to planners and decision makers in the hill area development.

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1. Introduction

1.1. Background of Research

Natural disasters are most unpredicted events which cause high loss to the society and property every year through out the world.

According to Emergency Management Disaster Database (EM-DAT 2009) the rate of occurrence of natural disasters has increased rapidly from 1900 to 2009 through out the world (Fig 1-3). The most affected year was 2000 and 2003 in which more than 500 natural disasters are reported by EM-DAT. According to EM-DAT, human and economic losses caused by natural disasters in 2008 were devastating. More than 235000 people were killed, 214 million people were affected and economic costs was over 190 billion US$ in which Asia remained the most affected continent. 40% of all reported natural disasters occurred in Asia as shown in (Table 1-1), more than 80% of the reported victims of natural disasters in 2008 are from Asia. The death toll was three times higher, and this was mainly caused by two types of events: Geological and Hydrological. Densely-populated countries frequently hit by natural disasters, such as China and India, reported high number of victims. This was most pronounced in India, where 10% of its total population, were affected by natural disasters in 2008. Among this 10% of total population, 0.5% of population are affected by landslides in India (EM-DAT 2009).

The term “landslide” basically means a slow to rapid downward movement of instable rock and debris masses under the action of gravity which can be categorised into various types on the basis of failure characteristics (Cruden, 1991). Vast expanse of areas in the country, particularly in the Himalaya and other hilly terrain, being highly fragile, is perennially under repeated threats of landslides and mass movements. Increase in population and rapid urbanization has led to expansion of construction activities in hilly terrain and has catapulted frequency of landslides to dramatic proportions in recent decades. Landslides are one of the major natural hazards that account for hundreds of lives besides enormous damage to properties and blocking the communication links every year. According to Geological Survey of India (GSI, 2009) 0.49 million km^2 or 15% of land area of the country is vulnerable to landslide hazard. Out of these 0.098 million km^2 is located in North-eastern Region and rest 80% is spread over Himalayas, Nilgiris, Ranchi Plateau and Eastern and Western Ghats. Especially in mountainous terrain the rain saturated steeper slopes are very much susceptible to landslides possessing direct risk to the properties, vehicles, and commuters. Other than direct risk these events possess indirect risk to the economical conditions of the society associated with these areas (Remondo, 2008).

Summarized Table of Mass movement wets sorted by Continent from 1900 to 2009					
		# of Events	Killed	Total Affected	Damage (US $)
Africa	Landslide	23	689	34,638	-
	ave. per event		30	1,506	-
America	Avalanche	4	95	154	-
	ave. per event		24	39	-
	Landslide	141	18,808	5,451,870	2,006,727
	ave. per event		133	38,666	14,232
Asia	Avalanche	40	2,277	53,992	50,000
	ave. per event		57	1,350	1,250
	Debris flow	1	106	-	-
	ave. per event		106	-	-
	Landslide	235	15,906	5,619,264	1,850,838
	ave. per event		68	23,914	7,876
	Subsidence	1	287	2,838	-
	ave. per event		287	2,838	-
Europe	Avalanche	34	1,247	13,145	774,889
	ave. per event		37	387	22,791
	Landslide	33	15,282	25,352	2,334,000
	ave. per event		463	778	70,727
Oceania	Landslide	17	486	20,315	2,466
	ave. per event		29	1,195	145

Table 1-1 showing the EMDAT database of continents from 1900 - 2009, (http://www.emdat.be/database)

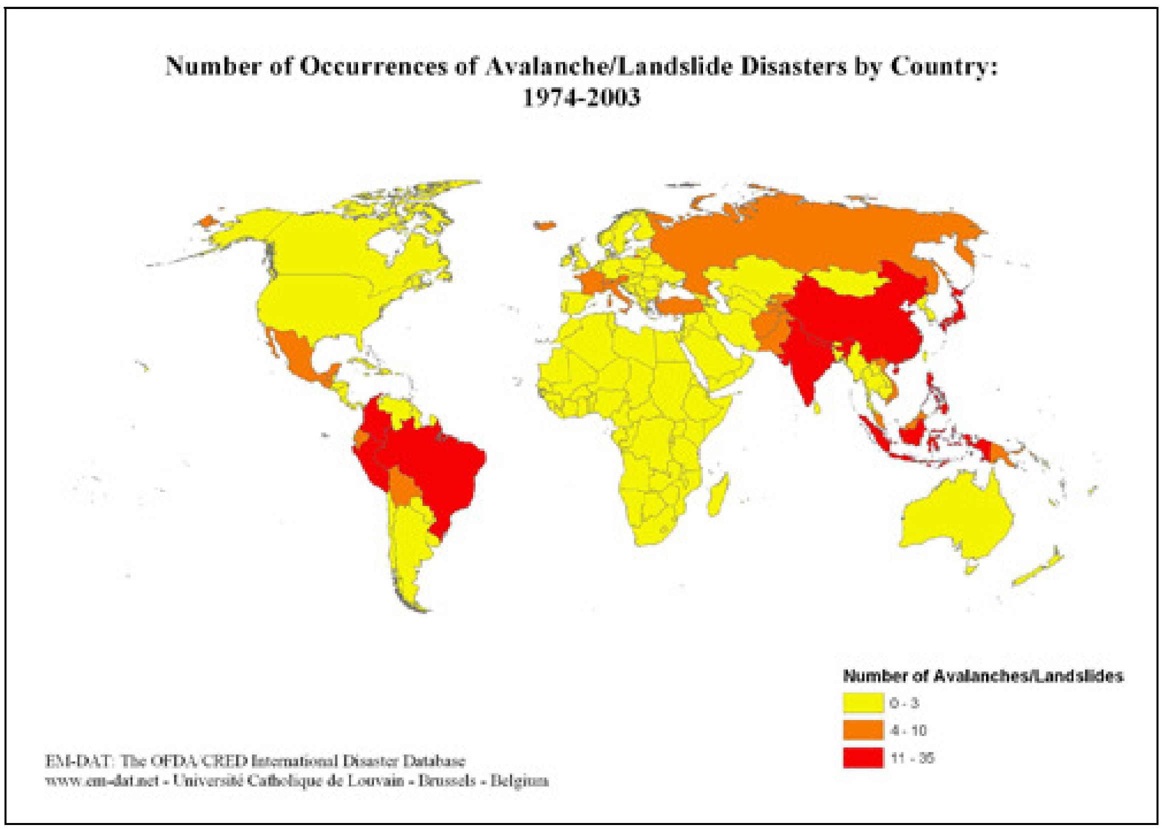

Figure 1-1 showing the map of EMDAT for Landslides and Avalanches from 1974-2005, (http://www.emdat.be/database)

1.2. Motivation

Landslides are the destructive and annual recurring phenomenon which causes disruption of traffic and fatalities. Every year during monsoon numerous landslides occur in the mountainous region of India. Landslides are one of the natural disasters which account for huge damage of properties in terms of direct and indirect risk (Dai *et al*. 2002). They are more frequent along the cut slopes of the transportation routes such as road corridors than the natural slopes causing damage to the property, vehicles, road and commuters along the road (Fig 1-2). Anthropogenic activities play an important role in rendering these excavated slopes unstable. During the construction of transportation routes the slopes are modified and left unsupported due to various reasons, including high treatment cost. During monsoon, rainfall initiates failure on these slopes. It increases the surface run-off on slopes, which passes into sub-surface layers through weak zones and increases pore water pressure of the soil or rock mass thereby causing failures (Terzaghi, 1950).

According to Geological Survey of India (GSI, 2009), the Darjeeling floods of 1968 destroyed vast areas of Sikkim and West Bengal by triggering some 20,000 landslides, killing thousands of people. These landslides occurred over a three day period with rainfall ranging from 500 to 1000 mm in an event of a 100 year return period. The 60km long mountain highway to Darjeeling got cut in 92 places resulting into total disruption of the communication link (GSI, 2009). Yet another landslide tragedy of unpredicted dimension was the Alaknanda Tragedy of July 1970 that resulted from the massive floods in river Alaknanda, upon breach of a landslide dam at its confluence with river Patal-Ganga. More recently, the Malpa rock landslide tragedy, hit headlines as it instantly killed 220 people and smash out the entire village of Malpa on the bank of river Kali in the Kumaun Himalaya (GSI, 2009).

Figure 1-2 showing the full damage of a bus during landslide in September 2009 on the road corridor

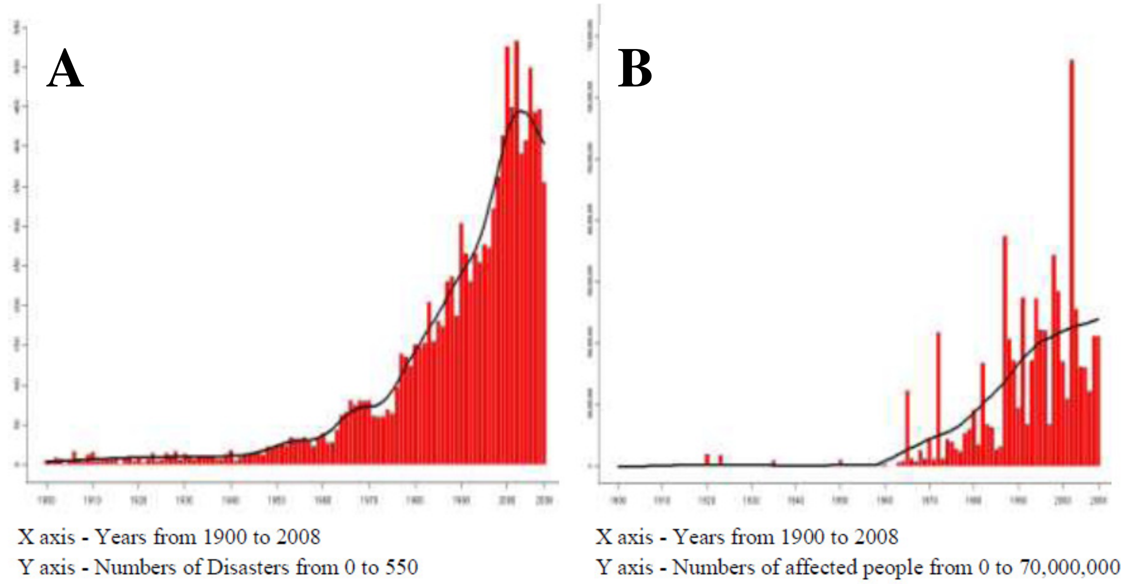

Figure 1-3 showing the increase in natural disaster from 1900 - 2008 (A) and number of people affected by the natural disaster (B), (http://www.emdat.be/database)

Uttarkashi earthquake on 20th October 1991 cause numerous landslides, particularly along a 27 km road stretch between Uttarkashi and Bhatwari (Sarkar and Gupta, 2005). One of the worst events happened in 1998; around 400 people were killed by large landslides near Okhimath and Malpa, in the Alaknanda Catchment (Kuthari, 2007). The Varunavat landslide in the Bhagirathi valley on the upslope of the Uttarkashi town makes the history by damaging a huge loss of both lives and property in the year 2003. On July-August 2004, a heavy downpour in Garhwal Himalaya caused debris slides and debris avalanches where at least 25 people died and 5000 people were stranded for days without food on the Joshimath-Badrinath road (Sahoo, 2009). Recently in September-2009 a tourist bus carrying 40 peoples to Gangotri from Uttarkashi was hit by landslide causing spot death to all the travellers as shown in (Fig 1-2).

Risk quantification of landslide is one of the major challenges in research for the scientist because of the uncertainty associated with its occurrence. Every year during monsoon landslides occurring from the steeper slopes above the road pose serious risk to the traffic and to the society. The risk can be direct resulting from the direct impact of the landslide to the vehicle or commuters or can be indirect due to the blockage of the road and shortage of supplies needed for day to day activities. As the landslides are inevitable their risk quantification appears to be the best solution to save the society from the danger of landslide. It will help the planners and decision makers to take an appropriate decision for landslide risk reduction.

1.3. Aims and Objective of the Research

Study mainly aims at quantifying the amount of direct and indirect risk from impact of landslides along a road in the Indian Himalaya. Direct risk is estimated for the road itself the different types of vehicles on the basis of different landslide types, magnitude and expected return periods. Indirect risk is generated due to the loss of income due to the blockage of the road by landslides for associated areas.

1.3.1. Main-Objective

The main objective is to carry out a detailed landslide risk assessment for a major road corridor in the Himalaya using historical landslide record and traffic analysis.

1.3.2. Sub-Objective

a) To generate comprehensive landslide inventory maps for the study area from 1994 to 2008 using historical landslide records, image interpretation and fieldwork.
b) To divide the study area into homogeneous mapping units with similar characteristic in terms of spatial and temporal landslide occurrence.
c) To generate hazard scenarios based on type, magnitudes of landslides and frequency of landslides.
d) To determine the vulnerability static and dynamic elements at risk.
e) To carry out risk assessment on different types of elements a risk on the basis of different hazard scenarios.

1.3.3. Research Questions

Question pertaining 1st Sub-Objective –

- Which satellite images should be taken for generation of landslide inventory?
- How a landslide inventory maps can be generated from historical landslide records?
- Is it possible to demarcate landslides polygons on the inventory maps from 1994 to 2007?

Question pertaining 2nd Sub-Objective –

- How large should be the upslope part of the mapping units, so that it incorporates all possible landslide areas that might affect the road.
- How the mapping units will affect the risk assessment method for the study area?

Question pertaining 3rd Sub-Objective –

- How the temporal probability should be the calculated for generation of hazard scenarios?
- Is it possible to make a direct hazard assessment for the road based on historical landslide data?

- Are the changes in the road configuration (e.g. new cut-slopes) such that it is possible to use past events for predicting future hazards?
- Is it possible to predict landslide frequency (number of landslides per mapping unit) using Poisson Distribution Model in the study area?
- Can landslides be sufficiently separated according to type and magnitude?
- Is it possible to make estimations for different return periods?

Questions pertaining 4th Sub-Objective –

- What is the relation between landslide magnitude and vulnerability for different vehicles and road?
- Which type of traffic information is required to do a vulnerability study of different vehicles and road?

Questions pertaining 5th Sub-Objective –

- How the hazard and vulnerability values can be integrated for risk assessment?
- How the value of risk will vary for different elements at risk?
- What type of value will be assigned for different elements at risk?

1.4. Thesis Outline

CHAPTER 1: Introduction

This chapter gives a general introduction about the background of the research, problems faced in landslide study and the reason or motivation behind the research. This chapter also highlights the aims and objectives of the research with research questions.

CHAPTER 2: Literature Review

This chapter briefs the previous work done on landslide risk assessment by various researchers, especially direct risk and indirect risk generated in different hazard scenarios for different elements at risk.

CHAPTER 3: Study Area

This chapter describes about the study area, geology, location, climate, major landcover, rainfall etc.

CHAPTER 4: Materials and Method

This chapter gives the idea about the material preparation for this research and detail methodology adopted for this research.

CHAPTER 5: Results and Discussion

This chapter discuss the result or the output of overall processing during the research: mainly the reasons of getting the result.

CHAPTER 6: Conclusions and Recommendations

This chapter summarises the result with conclusions and future recommendations for further work in ths research.

2. Literature Review

This chapter gives an idea about the previous studies of various researchers done in the field of landslides. Mostly this chapter will give emphasis on the various components of risk assessment i.e. landslide inventory preparation, spatial probability, temporal probability, identification of elements at risk, vulnerability assessment for these elements and finally with risk assessment. It will also give the definitions for the term landslides, classification followed by the possible causes of initiation of this kind of hazard.

2.1. Landslide: Type and Causes

Many physical scientist has given the definition for landslides in past. But the first definition was given Lyell in 1833 (Cruden, 1991). According to Lyell, landslides of present day are regarded as "landslips". He described these movements as "A portion of land that has slip down in consequence of disturbance by an earthquake or from being undermined by water washing away the lower beds which supported it". This definition of landslide has undergone many changes according to the development of science and technology. Now days, the term "landslide" describes a wide variety of processes that result in the downward and outward movement of slope-forming materials including rock, soil, artificial fill, or a combination of these by United States Geological Survey (USGS, 2004).

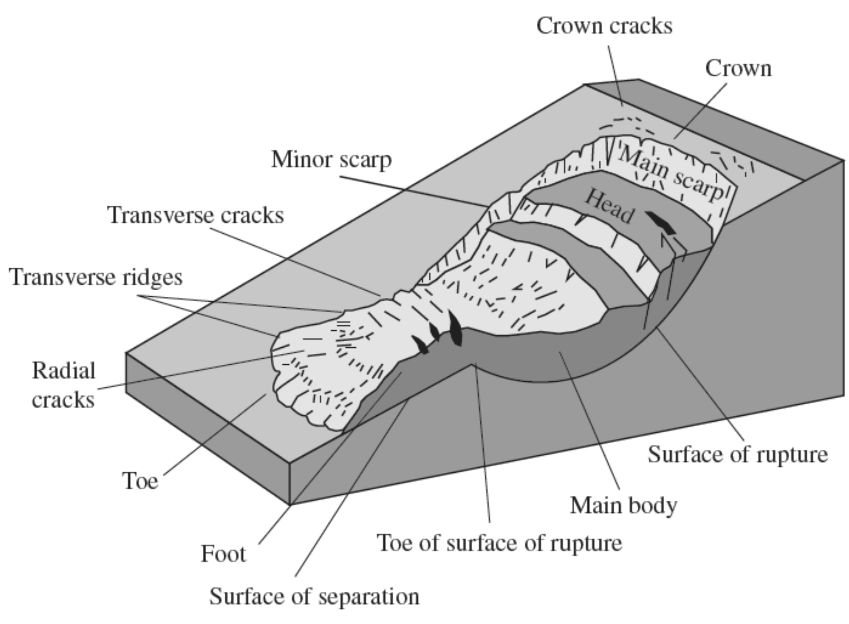

Figure 2-1 showing different parts of landslide (USGS, 2009) and (Chakraborty, 2008)

Landslides comprises of various types of movement (Varnes, 1984), which are complex in nature. Due to the complex nature of landslide movements these are classified into different types on the basis of their type of movement, style of failure, state of activity and type of distribution. The classifications of landslides are given below in (Table 2-1).

Type of Movement	Type of Activity	Type of Distribution	Type of Style
1) Fall	1) Active	1) Advancing	1) Complex
2) Topple	2) Reactive	2) Retrogressive	2) Composite
3) Slide : a) Rotational Slide, b) Translational Slide: i) Planar, ii) Block	3) Suspended	3) Widening	3) Multiple
4) Spread: a) Block, b) Liquefaction	4) Inactive	4) Progressive	
5) Flow	5) Dormant 6) Abandoned 7) Stabilized 8) Fossil/Ancient/Relict	5) Diminishing	4) Successive

Table 2-1 showing the classification of landslides (Varnes, 1984; Cruden, 1991)

Landslides are triggered events, and are caused when the surface conditions changes from stable condition to unstable conditions. The main cause of landslides is due to instability in slopes. This instability generates when the resisting force between two blocks is less than the driving force of the overburden, the gravity pulls the overburden in a downward movement causing failure. This kind of condition is generated due to various factors like shaking of earth surface, heavy rainfall, overburden on top of weak zone, heavy machineries movement (blasting or construction), deforestation, erosion etc. These causes are broadly categorised into geological, morphological and human by (USGS, 2004) in the (Table 2-2).

Geological causes	Morphological causes	Human causes
a) Weak or sensitive materials b) Weathered materials c) Sheared, jointed, or fissured materials d) Adversely oriented discontinuity (bedding, schistosity, fault, unconformity, contact, and so forth) e) Contrast in permeability and/or stiffness of materials	a) Tectonic or volcanic uplift b) Glacial rebound c) Fluvial, wave, or glacial erosion of slope toe or lateral margins d) Subterranean erosion (solution, piping) e) Deposition loading slope or its crest f) Vegetation removal (by fire, drought) g) Thawing h) Freeze-and-thaw weathering i) Shrink-and-swell weathering	a) Excavation of slope or its toe b) Loading of slope or its crest c) Drawdown (of reservoirs) d) Deforestation e) Irrigation f) Mining g) Artificial vibration h) Water leakage from utilities

Table 2-2 showing the various causes of landslides (source USGS-2004)

2.2. Landslide Studies in India

According to (GSI, 2009) landslides studies in India can be categorized into two groups (i) Pre-disaster studies and (ii) Post disaster studies. Organizations like Geological Survey of India (GSI), National Remote Sensing Centre (NRSC), Central Road Research Institute (CRRI), Central Building Research Institute (CBRI) and Wadia Institute of Himalayan Geology (WIHG) takes active participation in making of landslide studies in India. Above all Border Road Organisation (BRO) is also engaged in landslide activities mainly for the clearance of road and record maintenance. The pre-disaster studies are done by making different hazard zonation mapping of different parts of the country i.e. identifying susceptible zones for landslides in 1:50,000 to 1:5000 scale. This hazard zonation is done using methods using fuzzy gamma operator for Darjeeling Himalaya and Garhwal Himalaya by (Kanungo *et al.* 2006) and (Chamapatiray *et al.* 2007). Pre-disaster studies also include some of very few works in landslide risk zonation studies for India which is still in research and development mode. Scientist like (Pachauri *et al.* 2006) has done landslide risk zonation for Garhwal Himalaya using rock fall velocity as the primary tool, whereas (Kanungo *et al.* 2006) has also attempted a risk zonation for Darjeeling Himalaya using linguistic rule based fuzzy approach.

Post disaster studies is conducted by National Disaster Management Cell (NDMC) which include i) collection of data for landslide incidents, ii) preparing landslide inventory, iii) emergency response to landslide events and iv) supplying relief to the affected population in an area. This quick response to landslide and updating the records of landslides are really given a development in the field of landslides in India (Gupta K, 2005). Post disaster studies also include detail field survey of landslides places, preliminary monitoring of those landslides which are of bigger magnitude, slope stabilization of landslides which is done by laboratory sample analysis and details field investigation (Sharda, 2009). For the awareness of government and people living in landslide prone area special reports and newspapers articles are published. The records of landslides incidences for further studies are mainly recorded by BRO, CBRI, CRRI and GSI. Details of some of the impressive Pre and Post Disaster landslides studies of are carried out in various parts of India are as follows:

a) Details of pre assessment for debris and earth flow on national highway – 39 near Kohima, Nagaland (Kumar, K *et al.* 2008).
b) Stabilization procedures for Varunavrat landslide in Uttarkashi (2003) by GSI, BRO, CRRI, CBRI.
c) Landslide susceptibility using logistic regression and SSPC by (Sahoo, 2009) for the National Highway – 108 between Bhatwari to Gangnani.
d) Landslide temporal hazard scenario development the National Highway -108 using landslide inventory by (Chakraborty, 2008).
e) Quantitative landslide risk assessment along the communication link in Niligiri Hills by (Jaiswal, 2009).

The data availability in India for landslides risk assessment is the biggest barrier for the earth scientist. But still efforts are given to quantify risk from minimum available data.

2.3. Landslide Inventory

Any detailed studies on landslide risk assessment depends on collection of information about the landslides events, which is done by making a landslide mapping. A traditional way of landslide mapping is to generate a landslide inventory (Wieczorek, 1984) cited in (Guzzetti, 2005). According to (van Westen, 2000) landslide inventory is generated to have a good knowledge about the unstable area, a possible characterization of landslides on the basis of type or subtype and its activity. Landslide inventories are also done for gathering information on the basis of date of occurrence, location of occurrence (Guzzetti, 2005). Gathering information for landslide inventories are possible by maintainance of a good historical record of landslides. This kind of inventory directly gives an idea about the failure conditions of the unstable area approximately without making a hazard map (Hansen, 1984) which can gives precautionary support to the hazard area. Landslides inventories are very much essential component for landslides studies but still it require lot of time for data collection from field as well as from different organizations. The disadvantages of landslide inventory are, they donot give the temporal evolution of landslides where the change has takes place in due course of time (Parise, 2001).

As complied by (Guzzetti, 2005) from various litretures landslide inventory depends upon following assumptions:

a) Landslides occurrences leave traces or signs on the surface which can be traced using stereo images and aerial photos. These signatures refer to the change in form, position or appearance of the topographic surface. Some of the landslides give identifiable changes which can be mapped and measured using satellite imagery.
b) These morphological signatures of landslide depend on the type of its occurrence i.e. fall, slide, flow and rate of movement of slope failure.
c) Landslides are not occurred by chance. These are the result of the physical processes which can be determined by empirically, statistically or in deterministic fashion.
d) Landslides occurrences follow a principle of uniformitarianism "past and present are the key to the future". This implies that the future occurrences are more likely to occur under the conditions which led to past and present instability.

2.3.1. Landslide Mapping

The most important task in landslide risk assessment is the generation of inventory maps as the total study is highly dependent on the accuracy of mapping of landslides, also the data driven models used in landslide hazard assessment is based on the spatial correlation between the landslides and other thematic layers (Henriques, *et al.* 2009).

Remote sensing has given many researchers the benefit of mapping landslides from satellite images according to the necessity (Jaiswal, 2009). Mainly the stereoscopic satellite images has a ability to provide the characterization of landslides and three dimension perspective for the area (Chakraborthy, 2008). Landslides can be mapped in various ways using satellite images (Mantovani et al, 1996), aerial photographs (Turner and Schuster, 1996) and geomorphologic field mapping (Brunsden, 1993). But initially stereoscopic visual interpretation was widely accepted for landslide mapping, which requires lot of expertise on image interpretation techniques (Guzzetti, 2005).

Various techniques have been introduced by many scientists for extraction of landslides from satellite images and aerial photos which include image extraction from high spatial resolution satellite images, high spectral resolution images, digital stereoscopic image interpretation, landslide change detection method (van Westen, 2005). This is because of the wide coverage of a satellite image and repeated observation of a satellite and high spatial resolution which provides the best way for mapping landslides.

2.4. Terrain mapping units

Several methods have been proposed by various scientists to derive the ideal Terrain Mapping Unit (TMU) for landslide hazard zonation. These include grid-cells; terrain units; unique-condition units; slope-units; and topographic units. The choice of the mapping units is basically depends upon the purpose of study, location, type and size of landslide to be investigated and finally the capability of data handling tools (Chakraborthy, 2008). TMU refers to the portion of land which contain same set of thematic information as compared to the other adjacent areas (Guzzetti, 2005). According to (van Westen *et al.* 1997) TMU can also be formulated by integrating various thematic layers in GIS (i.e. lithology, geomorphology, landuse landcover, soil, slope) of a land surface. These units are generated from aerial photos and satellite images in GIS environment with the help of expert opinion and applying decision rules on the basis of landslides mapped during field investigation. And finally reclassified on there degree of susceptibility.

On the basis TMU many other researchers have tried to make partition of the land surface according to the suitability of there study. According to (van Westen *et al.* 1993) cited by (Guzzetti, 2005) give the concept of grid cell in which the terrain unit is represented by a single grid which are rectangular, square, triangle or hexagonal in size. But main disadvantage is grid cell are too small to characterize the terrain features.

(Hansen, *et al.* 1995) give the concept of terrain units which is traditionally favoured by geomorphologist. These units give the relation between materials, forms and natural processes which is highly useful for geologist and geomorphologist.

(Guzzetti, *et al.* 1999) proposed the concept of slope units. These units are identified from normal topographic maps and can be derived automatically from high quality DTMs. These units are very much useful as it gives a good quality of subdivisions for a terrain. Slope units also derive the morphometric and hydrological parameters which helps in determining the susceptibility of the terrain. The problem with this kind of unit is it requires specialized software for its preparation, difficulty in making its size as compared to a landslide, it doesn't give any representation for small landslides. The later problem was solved by the author by making more subdivisions on the basis of lithology and drainage divisions of the terrain.

(Pasuto and Soldati, 1999) introduced an innovative method by considering the spatial and temporal relation for mapping gravitational deposits and by grouped these into homogeneous units called landslide units. These units provide surface analysis and provide an efficient information about the terrain which are quite complex in case of geomorphological mapping. Landslide units are also important for application purpose which gives simple result for non-specialist as referred by the author.

2.5. Landslide Hazard

Landslide hazard estimation is a complex process which require different techniques and methodologies, and lot of expertise (Hungr, 1997). A hazard by definition is the probability of occurrence of landslide of a particular magnitude (Malamud, *et al.* 2004), in a particular place in a given time (Varnes, 1984). This concept of hazard reflect the place of occurrence (where ?), time of occurrence (when ?), and magnitude (how big ?) (Cardinalli, *et al.* 2002).

2.5.1. Spatial Probability - Place of Occurrence (where?)

Spatial probability of landslide hazard (susceptibility) analysis has been estimated in the past by various indirect methods i.e. statistical method (data driven) techniques, in which landslide influencing factors (such as slope, rock type, landform and land-use) are ranked and weighted according to their assumed or expected importance in causing slope failure (van Westen *et al*, 2005). These methods are basically quantitative and done for the (Sahoo, 2009) done slope stability analysis using logistic regression and SSPC probability model (Hack, 1996) for National Highway - 108 in Uttarkashi district, where the author used the different variable classes of drainage, lithology, lineament, soil depth, weathering and slope as independent variables and landslides as dependent variables along the road corridor and found out the probability for each pixel in the study area, also taken 32 slopes faces and obtained the probability for different sections of the road using SSPC model. (Guzzetti, *et al.* 2005) estimated the landslide susceptibility using discriminant model for 46 thematic variables. The probability for each mapping unit was obtained by computing the percentage of influence in each thematic variable in a GIS environment.

Some of the methods are directly done from geomorphologic mapping, in which past and present landslides are identified and assumptions are made on the factors leading to instability; and zonation are made on the basis of their failure conditions (Soeters and van Westen, 1996). According to the Joint Technical Committee - 1 (JTC-1) (Fell, *et al.* 2008), landslide susceptibility zoning should be done on the basis of past landslide occurrence, excluding the areas of the old and dormant slides, different types of landslides should be recognized which may have different susceptibility factor (i.e. debris slide , rock slide etc) and area not having the landslides in past history but topographic conditions indicate the same environmental factors should be taken into consideration. These direct methods of landslide susceptibility zoning are normally based on knowledge available to experts on various causes of landslides in the area of investigation.

2.5.2. Temporal Probability - Expected probability on given time (when?)

The most important estimation of landslide hazard assessment is the time of occurrence or the probability of occurrence of a landslide in a given time. This probability of occurrence of landslide can be obtained by direct and indirect methods. Indirect method of obtaining temporal probability for landslides can be estimated by deriving the relationship between the landslide trigger and the occurrence of landslide in the past (Jaiswal, *et al.* 2009). This is done on the basis of antecedent rainfall, rainfall duration, rainfall intensity or cumulative rainfall which gives a threshold value for the minimum rainfall for which a landslide will trigger and on the basis of this threshold the return period is calculated for landslides.

Direct methods are data driven methods which basically runs on the basis of number of occurrences of an event. (Crovelli, 2000) and (Guzzetti, *et al.* 2005) used the Poisson probability model to found out the expected occurrence probability of landslide in an expected time. Various other researchers also use this model to find out the expected recurrence intervals of volcanic eruption (Nathenson, 2001), flood (Coe, *et al.* 2000). (Chakraborty, 2008) used this model to found the expected landslide occurrence probability in a given time period for a road corridor, where she divided the road section into 23 units and calculated the number of landslide occurrence for each road unit on the basis of 5 years landslide inventory.

2.5.3. Landslide Magnitude - Intensity of the event (how big?)

Landslide is natural complex phenomenon which generate serious natural hazard throughout the world. From various literature reviews it was studied that a quantitative classification of landslide magnitude requires landslide volume data from historical records during the preparation of inventory, which is actually not available for many landslide prone areas in the world. Magnitude of landslide is the most important component in landslides risk assessment as magnitude decides the damage factor to any elements at risk due to a landslide in a given time. According to (van Westen *et al.* 2005) the damage factor of landslide of a particular volume to any elements at risk is highly dependent on the run-out distance of landslide. Higher the magnitude, higher is the run-out and higher is risk. In order to quantify the effect of this phenomenon, the probability of particular landslide magnitude occurrence should be considered for landslide hazard estimation (Malamud, *et al.* 2004; Guzzetti, *et al.* 2005). In these literatures the author determines the probability of landslide size using truncated inverse gamma probability distribution function and probability density function. This result gives the prediction of individual landslides for Collazzone area.

(Hungr, *et al.* 1999) gave a cumulative frequency volume distribution for 1937 rock falls and rock slides in four sub-divided area of south-western Columbia where he got the negative power-laws with 0.5 to 0.2. (Dai and Lee, 2001) surveyed 2811 landslides, mainly rock falls in Hong Kong in the period of 1992-1997 and found the cumulative frequency-volume distribution with a negative power-law of 0.8.

Other than the quantitative classification of landslide magnitude, qualitative classifications of magnitudes are also considered for risk assessment in various researches. (Pierson, 1998) has given a size classification of wet debris flows and found the relation between the velocity and flow magnitude. He differentiated the debris flows between the volumes as moderate (10^2 to 10^3 m^3/s), large (10^3 to 10^4 m^3/s), very large (10^4 to 10^6 m^3/s) and extremely large ($>10^6$ m^3/s). Describing the size of landslide volumes is insufficient in hazard and risk assessment. It is also important to the area that will be inundated by a particular volume of landslide (Jacob, 2005). Estimation of area inundation can be done on the basis of field investigations and previous records of landslides events in a particular place which can directly used in risk assessment. A magnitude class was proposed by (Jaiswal, *et al.* 2009). The magnitude class has five types of classes ranging from I (less severe) to V (catastrophic). This classification was based on type of landslide, landslide volume and characteristic such as location, source, damage potential, human perception and field investigation. As mentioned by the author this classification is semi-quantitative and derived on the basis of past records of occurrence of landslides during preparation of inventory.

2.6. Vulnerability Assessment

Vulnerability is a fundamental component in the evaluation of landslide Risk (Leone, *et al.* 1996) which is defined as the level of potential damage, or degree of loss, of a given element (expressed in scale of 0 to 1) subjected to a landslide of given intensity (Fell, 1994; Wong, 1997). From various literatures it was studied that till now there is no such concrete method to determine the probability of damage. Vulnerability of different elements at risk for landslide is still a challenge for many scientists.

(Dai *et al.* 2002) given the concept of landslide vulnerability in a subjective manner which mainly depends on the historical damage records, traffic density, run-out distance of landslides, its volume, velocity of sliding, nature of type of elements at risk and their proximity to a slide. (Galli, and Guzzetti. F 2007) have studied the vulnerability of landslide in Umbria province in central Italy. The study concentrated to estimate the degree of loss on building and road by taking assuming the elements at risk are permanent and fixed. A power law function was applied to establish the upper and lower threshold to generate the vulnerability curve. (Guzzetti, 2005) estimated the degree of vulnerability for dynamic elements in same study by using the Average Vehicles at Risk (AVR), where he calculated the approximate number of expected vehicles at particular time in a particular portion of land. This calculation of density of vehicles is done on the basis of traffic density in the area.

(Birkmann, 2007) has given the concept of vulnerability in terms of different vulnerability spheres, starting from vulnerability as internal risk factors (Intrinsic vulnerability) to Multi-Dimensional vulnerability encompassing physical, social, economic, environmental and institutional feature. The vulnerability sphere is given below in (Fig 2-3)

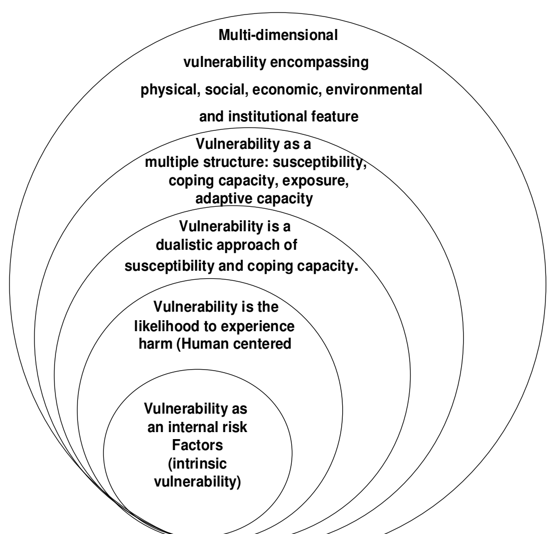

Figure 2-2 showing the vulnerability spheres by (Birkmann. J. 2007)

(Uzielli, *et al.* 2008) given a scenario based, quantitative approach for estimating the physical vulnerability of build areas and also proposed an uncertainty analysis in vulnerability estimation. They proposed this method on the basis of landslide intensity and susceptibility of elements at risk, where landslide intensity is estimated on the basis of its destructiveness to any elements at risk which depends on velocity, run-out distance, depth of the moving mass, unit discharge, kinetic energy per unit area and maximum and normal or shear strain (Hungr, 1997). The susceptibility of elements at risk in this literature refers to the spatial relation between the landslide mass and elements at risk.

(United Nations Development Program, 2004) classified the vulnerability into four major categories according to the damage done by any event:

i) Physical vulnerability - This indicate the physical damage to the property or infrastructure of any fixed amount.
ii) Environmental vulnerability - gives the loss due to damage of natural resources, mainly landuse and landcover.
iii) Social vulnerability - indicates the loss due to death of people and any social damage concerned with the hazardous event.
iv) Economical vulnerability - affects the economic condition of the hazardous area and measured on the basis of gross domestic product (GDP), this concept of vulnerability is estimated for indirect risk method.

(Remondo, 2008) done a vulnerability assessment from detailed analysis of past damage from landslides. They prepare an inventory of from field surveys and public interviews from private institutions, municipalities, transport and finance departments, insurance and construction companies regarding the past damage done by any slide. The author made a vulnerability matrix of landslide intensity or magnitude against landslide type and estimates the vulnerability for each element on the basis of total loss due of an element at risk of a particular type upon cost of that element at risk (Leone, *et al.* 1996; Dai, *et al.* 2002).

According to (Liu, 2006) vulnerability grows rapidly with increase in population and property in any hazardous area. But some time this growth decrease with increase in loss to property than population. He derives an equation for estimating vulnerability based on statistical analysis on population, buildings, infrastructures, economic activities and social structures in southwest china. In his research he proposed that vulnerability is a sum function of both property and population index which have different measurements and are actually transformation functions. The property index, which is a sigmoid curve, gives the vulnerability value according to the density of infrastructure. The population index is a poison curve estimates the vulnerability value for expected number of population in a landslide zone.

2.7. Landslide Risk Assessment

Many earth scientists throughout the world are working on risk assessment of landslides. In strict sense landslide risk can be defined as “the expected number of lives lost, person injured, damage to property, and disruption of economic activity due to a particular damaging phenomenon for a given area and reference period”(Varnes, 1984) cited by (van Westen, *et al.* 2005). In the past few years the major field of research in risk assessment is done on the spatio-temporal aspect of landslides, and on the variations in vulnerability of the elements at risk. The basic formula for risk assessment is product of hazard, vulnerability and amount ”(Varnes, 1984; Fell,1994). According to (van Westen, *et al.* 2005) obtaining specific landslide risk with this simple formula for any element at risk is quite complex, which require a lot of past record and various information about the landslide as shown in (Fig 2-4). This concept of risk was changed after (Guzzetti, 2005), where he redefine that landslide risk is the product of spatial probability, temporal probability and magnitude of its occurrence which change the degree of vulnerability for different elements at risk. Risk due to landslides is mainly depends on the proximity of elements at risk from a landslide event. Direct impact of landslide to the exposed elements at risk possesses higher risk called as Direct Risk and the loss occurred due to the blockage of communication link, which affects the associated areas can be called as Indirect Risk.

Landslide risk can be estimated by Heuristic, Statistical and Deterministic method. On the basis of these methods landslide risk assessment can be quantitative or qualitative and also depends on the input data, which include historical information like frequency of occurrence, location, damage done by particular type of slide (van Westen *et al.* 2005). Based on the processing method and input data landslide risk assessment can be sub-divided into two broad types: Qualitative and Quantitative landslide risk assessment.

2.7.1. Qualitative Landslide Risk Assessment

Qualitative landslide risk assessment is done on the basis of direct method i.e. geomorphological mapping, or indirectly by combination of qualitative maps generated from expert opinions, and knowledge based analysis (van Westen *et al.* 2005; Fell, *et al.* 2008). The authors mentioned in these literatures that a qualitative risk assessment of landslide is prepared by heuristic method, geomorphic mapping and map combination method. Lack of record about the occurrences of landslides also gives a qualitative hazard map without any temporal component in it, which directly result into a qualitative risk map. According to (Dai *et al.* 2002), heuristic approaches are done to estimate the landslide potential zones on the basis of preparatory variables. This process is based on assumptions which indicate the relation between landslide susceptibility and variables. These input variables for processed in a landslide susceptibility model with an output as weight map for different preparatory variables. These weight maps are then classified on the basis of expert opinion or on the landslide density as high, moderate and low. As mentioned by the author the drawback of this method is the weighting and ranking of the variables which is highly subjective.

(Cardinali, *et al.* 2002) proposed a geomorphological approach to achieve a qualitative landslide risk map. On studying the local geological, geomorphological and past landslides record setting they mapped the present and past landslides for Umbria, Italy. The mapping of landslides is done on stereo interpretation of aerial photographs available and field investigation. The author detects the changes from multi-temporal inventory by studying the past and present landslides, which gave them the idea of generation of new slopes, different types of failures and intensity of landslides. On basis of this information, hazard and risk zonation are made for the study area. In this literature the author also suggest that this method of geomorphological mapping requires a trained geomorphologist.

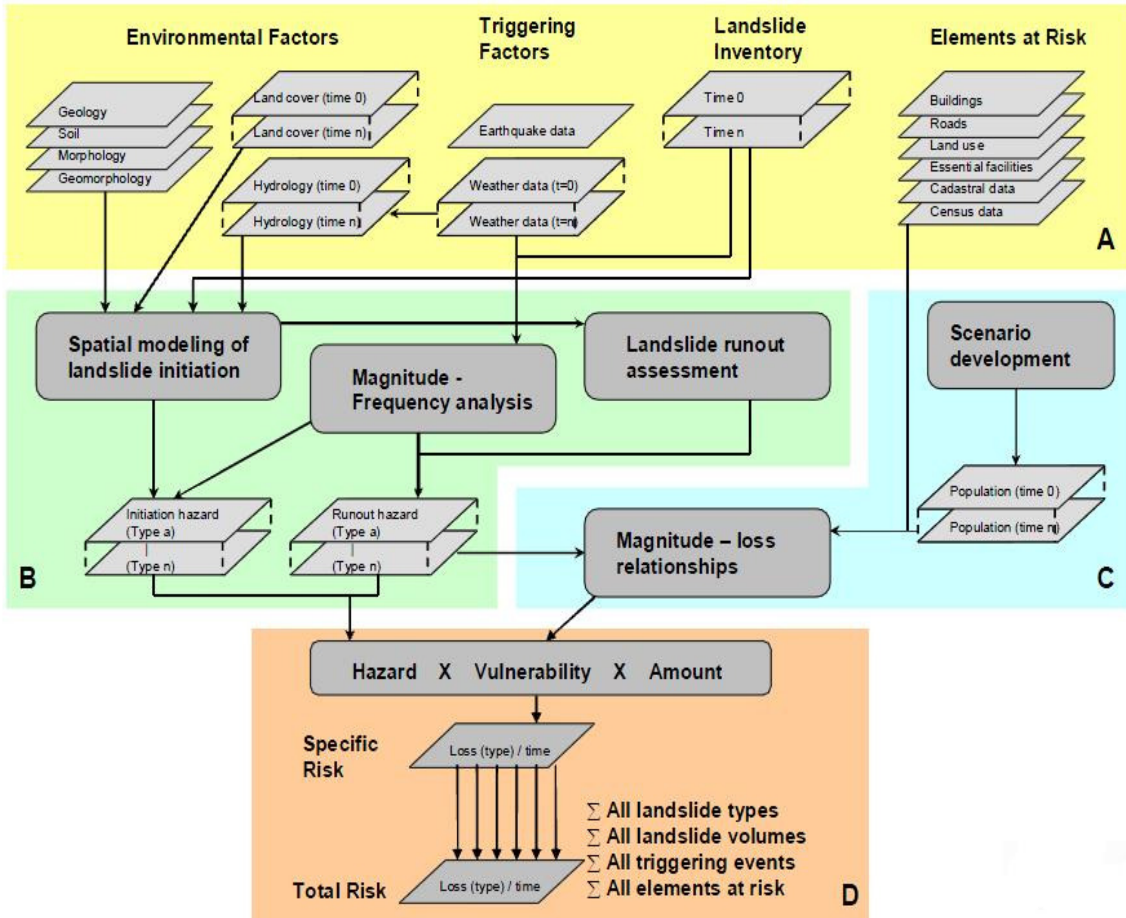

Figure 2-3 describing the different sections (A, B, C and D) of the flow diagram for landslide risk assessment. (van Westen *et al.* 2005)

According to (van Westen *et al.* 2005; Fell, *et al.* 2008), Statistical approaches are a basically probabilistic method which provides the relation between various factors individually and the distribution of landslides. This method is used in data integration techniques in a GIS environment where the factors maps are integrated with the landslide inventory map to achieve the probability of each factor map on the basis of landslide distribution (van Westen *et al.* 1993). The probability of factors maps are determined by statistical method which finds the interrelationship between the factors map and instable zones, which results in probabilistic hazard zonation of the area. Statistical methods has a main drawback as it doesn't provide a reliable dataset which can have errors during mapping from poor resolution of satellite images and incomplete inventory and also these methods are very much site specific (Fell, *et al.* 2008). Another drawback of this method is that it doesn't provide much information about the temporal occurrence of the landslides (van Westen *et al.* 2005) for which it cannot be used in quantitative landslide risk assessment.

(Zerere *et al.* 2008) proposed a probabilistic landslide risk analysis including the direct cost to buildings in a small area of 20 km^2 using statistical analysis in north of Lisbon, Portugal. The authors generate a scenario based risk assessment on different types of landslides types (i.e. shallow translational slides, translational types and rotational types). Evaluation of likelihood of the landslides is done on the basis of past distribution of landslides by using statistical method. On the basis of rainfall triggers, return period is calculated and various scenarios are developed for 2561 buildings and road in 169 km. Vulnerability values are determined by magnitude of each type of landslides. All these operations are done in raster based calculation by the process of map integration technique in a GIS environment.

Till present date various methods have been proposed by lot of scientists for qualitative landslide risk assessment depending on the problem encountered and area of interest. Generally qualitative landslide risk assessment is done for larger areas to achieve a broad idea about the area or for those areas where details data collection for landslides is difficult. Qualitative methods are basically done on the basis of individual expertise or by field investigation, which provides enough reliable information in very low cost than quantitative methods (van Westen, 2005).

2.7.2. Quantitative Landslide Risk Assessment

Quantitative landslide risk assessment is basically done by deterministic method. These methods estimate the loss in terms of probability providing best result. Quantitative risk assessment is basically done for an area with a small scale to have a systematic assessment of hazard, vulnerability and different levels of risk in terms of loss and fatality (i.e. monetary value and probability respectively), which can result in good risk management and mitigation approach for planners (Dai *et al.* 2002).

According to (van Westen *et al.* 2005) deterministic models are generally done using slope stability models to determine the relation between the factors of safety rainfall induced landslides. As mentioned by the author processing of these models is highly dependent on large amount of input data required which is prepared from field investigation and laboratory test. These models deliver its best when it is processed for a small dataset in a large scale. Deterministic models can simulate the run-out behavior of landslides with dynamic hydrological modeling by estimating the pore water pressure.

As mentioned in (Dai, *et al.* 2002), event tree method (Wu, *et al.* 1996) can also used in quantitative risk assessment for landslides. This event tree method is processed, where the run-out behavior and probability of landslides for different types of landslides are estimated and vulnerability values are estimated and finally all these parameters given as inputs to the event tree, to quantify the risk.

A quantitative risk assessment for landslides is proposed by (Jaiswal *et al.* 2009) in parts of Nilgiri hills of Southern India. As mentioned by the author quantitative direct risk estimation was evaluated in various scenarios for different elements at risk like: railway track, vehicles and commuters on the road and road itself on the basis of 4 types of magnitudes and 3 types of landslides in different return periods generated from a complete landslide inventory. For magnitude calculation the author prefers geological field investigation during the preparation of landslide inventory. Indirect risk is also calculated for the associated areas in this article on road blockage by the impact of landslide. The indirect risk calculation was in terms of: i) extra fuel consumption, ii) extra travel time by alternate way, iii) extra cost for travelling in alternate way.

(Remondo, 2008) proposed a quantitative method for estimation of direct and indirect risk on the basis of analysis and mapping in a GIS environment. This method of risk estimation is based on a susceptibility model done by (Remondo *et al.* 2003) where statistical relationship was estimated by means of previous landslides and terrain parameters. To identify and carry out the loss for different elements at risk the author mapped a detailed inventory of different elements at risk and direct damage to the risk elements due to landslides occurred in the past. Vulnerability was estimated on the basis of loss with the actual value of different elements at risk. Finally a risk map was generated combining hazard, vulnerability and amount showing 2.4×10^6 euro of loss for different elements including direct and indirect impact of landslides for 50 year return period.

Detail literature review reveals that a landslide risk assessment is a process which looks simple theoretically but in reality it is very much difficult to evaluate. Till now no such concrete method was proposed to evaluate a quantitative landslide risk as the landslide are discrete phenomenon which occur in a random order. Because of this randomness the estimation of vulnerability for different elements are also difficult. Apart from this a quantitative landslide risk assessment needs a huge amount of data collection from the field and a lot of expertise is required for interpreting the landslide behavior and characteristics.

3. Study Area

The study area was selected on the basis of major landslide active zones in the country. According to GSI 15% of land area in our country is vulnerable to landslides where 80% of this 15% land area is spread over Himalayas range and rest 20% is on different parts of the country (GSI, 2009). The occurrences of landslides in Himalayan region are mainly on the road corridors blocking the communication link and possess high risk to the society. So, southern belt of Himalayan region i.e. Uttarakhand was selected for the study of this research where each year landslide event damage road, property and possess high threat to the society. The study area was selected on the basis of following criteria:

i) The degree of necessity of risk assessment for the study area.
ii) Availability of high resolution satellite images for the study area.
iii) An updated record for different landslide occurrences for the study area.

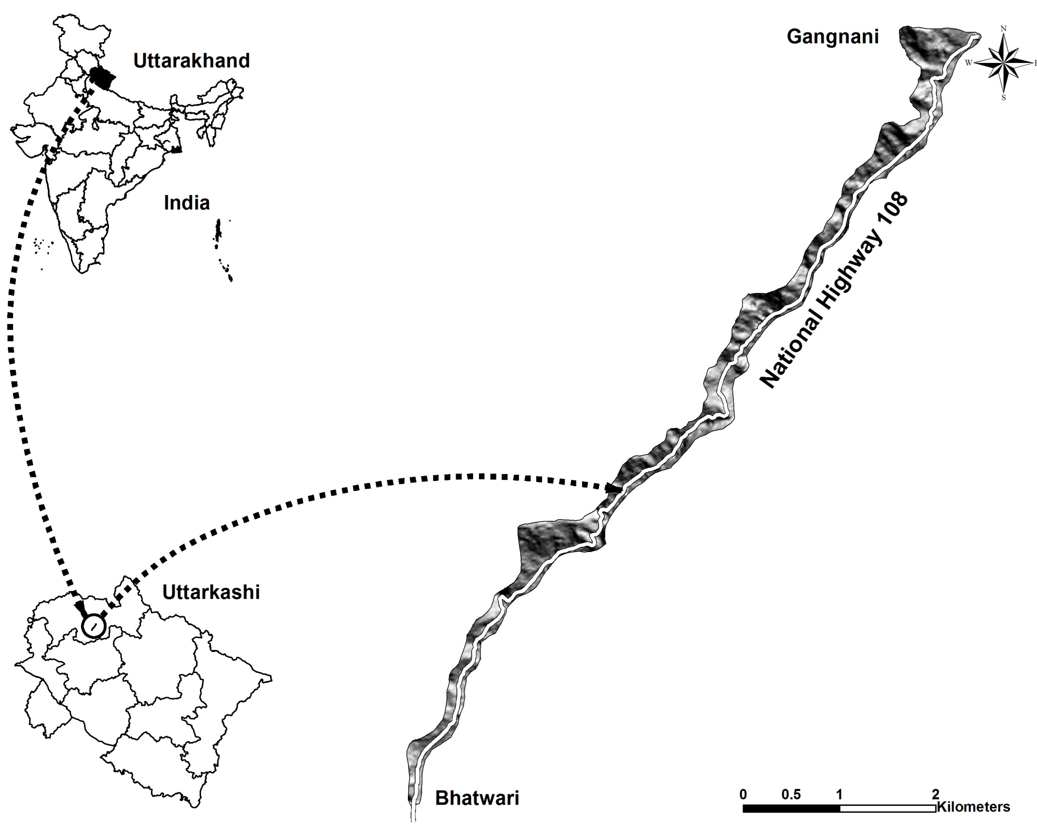

Figure 3-1 showing the study area and the major road corridor (National Highway - 108)

3.1. Uttarakhand

The study area as shown in (Fig 3-1) is chosen for this research is the road corridor of National Highway - 108 passing through the terrain above Bhagirathi River from Dharasu to Gangotri in Uttarakhand State. Uttarakhand is one of the religious state of India which comes under $30^0 15^'$ N to 79^0 $15^'$ E. This state covers 51,125 km^2, in which 93% is highly mountainous and 64% is covered with forest.

The term Uttarakhand is derived from Sanskrit term (Northern country) which forms 27^{th} state of Republic India in the year 1999. This state has changed its name from Uttaranchal to Uttarakhand in January 2007. Uttarakhand state is divided into two divisions: Kumaun Division and Garhwal Division. The study area is under provinces of Garhwal division in Uttarkashi district where the physiographic conditions and fragile landscape triggers maximum geological hazard in which landslides events are most frequent. Most of the northern parts of this state are part of Greater Himalaya Ranges and lower foothills are covered by forest. The total population of Uttarakhand is approximately 8.48 million which is quite low as compared to the other states in the country. Uttarakhand also share the border with China (Tibet) in the northern part and Nepal in the eastern part. Apart from this Uttarakhand is highly religious and famous for its scenic beauty which attracts tourists from all over the world. Two main rivers of India, the Ganga and the Yamuna take birth in the glaciers of Uttarakhand.

3.2. National Highway - 108

National Highway - 108 is one of the major routes for northern region of Uttarakhand state. The road corridor for this research covers 2.65 km^2 area in 11 km long stretch in between the latitude 30^0 48' 02" N to 30^0 50' 53" N and longitude 78^0 36' 04" E to 78^0 48' 05" E along the fast flowing Bhagirathi river valley (Fig 3-2) in Garhwal Himalayas joining Bhatwari (56.5 km) at southern end and Gangnani (67.9 km) at northern end.

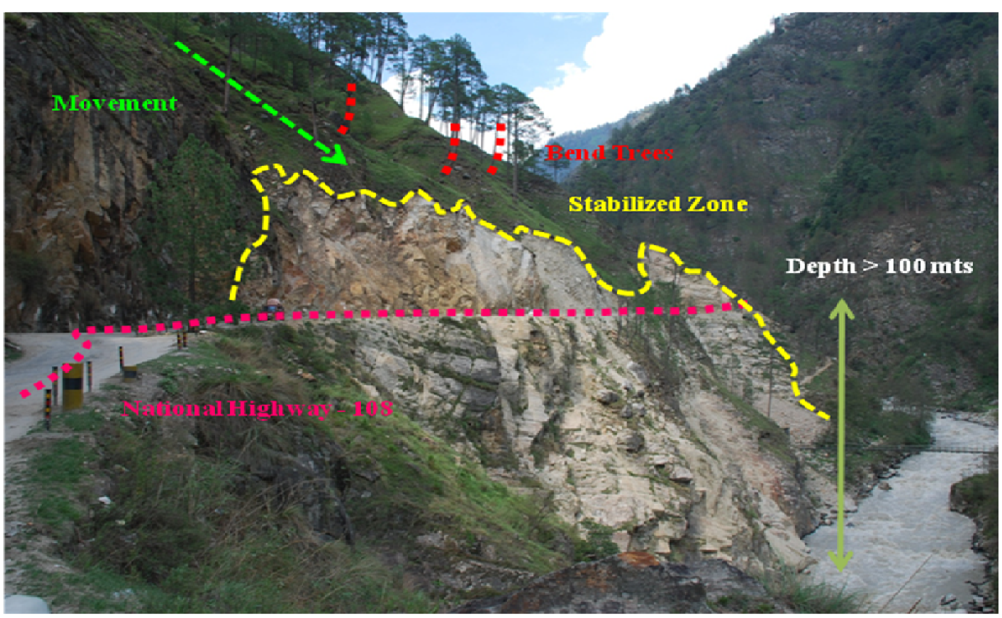

Figure 3-2 showing the part of the road corridor from Bhatwari to Gangnani

This highway originates in national highway - 94 from Dharasu and connects upto Gangotri. This Route from Dharasu to Gangotri is one of the religious routes for Indian culture and heritage which attracts thousands of pilgrims and tourists across the country and from different parts of the world during the month of August, September and October which is regarded as the auspicious time for offerings to god. Other months in the year remains with less traffic as population density is very low for this place and Gangotri is also closed for rest of the months due to snow cover. As this road corridor has a maximum elevation level of 2500 mts and minimum level of 1500 mts it receives rainfall intensity of 1200mm per year for the month of August, September and October which trigger frequent landslides every year. This place rainfall intensity along this particular National Highway is 70% of the total rainfall from other area in the state.

As this highway is one of the major life-line for the northern Uttarakhand the landslides in this road stretch cause disruption in the communication link for pilgrims and tourists visiting the Gangotri and also possess high risk for the vehicles, commuters and property along the road corridor during August, September and October. This road stretch of 11km from Bhatwari to Gangnani in this highway is 4 to 5 meter wide so any type of disruption in the communication link will cause severe economic loss and moral loss to the society as it is the only way reach Gangotri during the festive months.

3.2.1. Climate and Rainfall

The study area experiences a subtropical temperate climate throughout the year because of its high altitude. The type of climate found in this area as equivalent to Gangetic plain. The study area experiences 40^0 in summers considerably humid and below 5^0 in winters which is quite chilly. The maximum elevation in the study area is 4500 m from mean sea level and minimum of 1150 m. Certain places in this area is inaccessible because of the snow cover in the month of October, November and December. This road corridor has a maximum of 2500m to 1500m elevation from mean sea level so the rainfall intensity is very high approximately 1200mm in a year for the month of August, September and October. The rain gauge stations in the study area are place in Uttarkashi, Tekla, Malla, Maneri, Gyansu, Bhatwari, Jaurab, Bankholi and Gangotri. The maximum rainfall experiences in this area is about 1700mm to minimum of 1155mm in last two decades (BRO, 2009). The average rainfall from 1988 to 2008 is shown in (Fig 3-3).

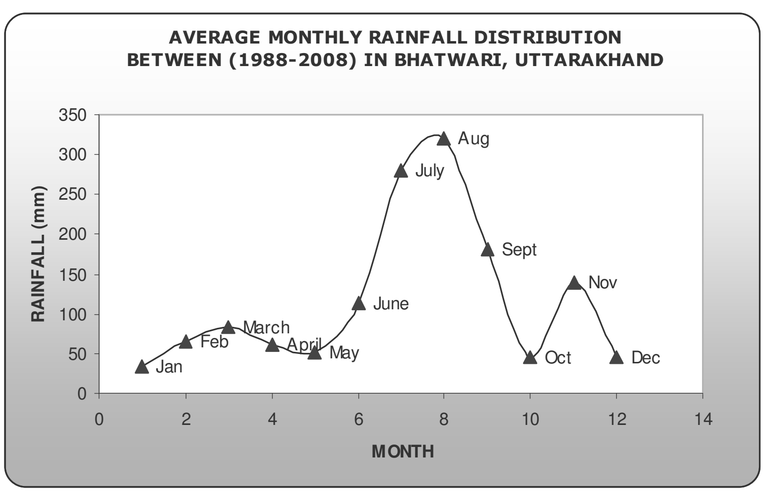

Figure 3-3 showing the average rainfall from 1988 to 2008 for the study area (Sahoo, 2009)

3.2.2. Geomorphology

The major geomorphic features observed in the study area are of structural, glacial, fluvial, and denudational in origin. Metamorphic rocks have an inverted relief which gives an idea of active weathering process in the study area. Cuesta and hogbacks type topography, river terraces, highly dissected denudo-structural hill (Fig 3-4), intermonatane valley, minor and major ridges of quaternary deposits and various geomorphic features like point bar, channel bar, meandering scars are observed along the entire river course. Deep gorges and wide valleys engraved high relief are structural control of the area. The narrow and confined nature of the valley towards the lower portion of the stream indicates the continued erosional nature of these valleys. The middle valley slope generally consists of periglacial and hill slopes scree, landslides and old rock falls.

Figure 3-4 showing the river terraces (A), and Dissected denudo-structural hill (B) along Bhagirathi river

3.2.3. Drainage

The study area is one of the holiest places of India because of the streams like "Ganges" also known as Bhagirathi originates at the northern part. It originates at Gangotri glacier in Gaumukh in Tethys Himalaya forming a broad U-shaped valley near Jhala at its upper course. Afterwards it continues to cut the deep V-shaped gorges while flowing through Greater and Lesser Himalayan course. The river is fed with numerous small first and second order streams from both the sides. Dendritic drainage pattern is predominant over the area and also sub parallel pattern is observed along the hill slopes. The entire road stretch of National Highway 108 is running parallel to the river Bhagirathi.

3.2.4. Natural Vegetation

The study area is well known for its natural vegetation and quite similar with the Himalayan biogeography. The sub-tropical zone of the study area has as pure as mixed forest. The high altitudinal zones of the area characterized with beautiful pasture lands which contains grasses with plants, like Piceasp, Pinus, Cesrus, Deodar, Karsu, Quereus semecarpifolia, Rhohododendrron, Camapanualatum, and Betulautilus etc. the moderate to lower altitudinal slopes are generally used in step cultivation for growing potatoes. The natural vegetation predominant over these slopes is Shores robusta and Dalbegia sisoo.

3.2.5. Soil

The study area has various type of soil, all of which are susceptible to soil erosion. In the northern part, the soil ranges from gravel (debris from glaciers) to stiff clay while the southern part is characterized by soils that are course-textured, sandy to gravely, high porous and largely infertile. The total soil cover is existing as a thin layer along the slopes. While the road corridor under geomorphic units like river terraces have thick soil cover where cultivations are practised in abundance. Depending upon these altitudes and geomorphic conditions, the change in soil characteristic is noticeable in the area. Very steep slopes are mostly left without any soil cover.

3.2.6. Anthropogenic Effects

This road corridor is maintained regularly for the stabilization of landslides which include movement of heavy machineries and blasting of overhanging and steep lying rock beds. Many times these civil engineering maintenance leads to new slope failures. It has been observed in several places road passes through half tunnels, overhanging slopes portions are left unprotected. These overhanging portions can be observed several places especially between Thrang to Gangnani (around 5 kilo meters road stretch), which also very prone to landslide activities (Fig 3-5). This road stretch passes through Gneisses and schist, which show the presence of joints in overhanging portions are almost vulnerable and dangerous features. At some places explosives used for blasting as carried out in construction and widening of the road produce vibrations of different frequencies in rocks and thus a temporary change in stress can disturb the equilibrium state of the slope further resulting in slope failure.

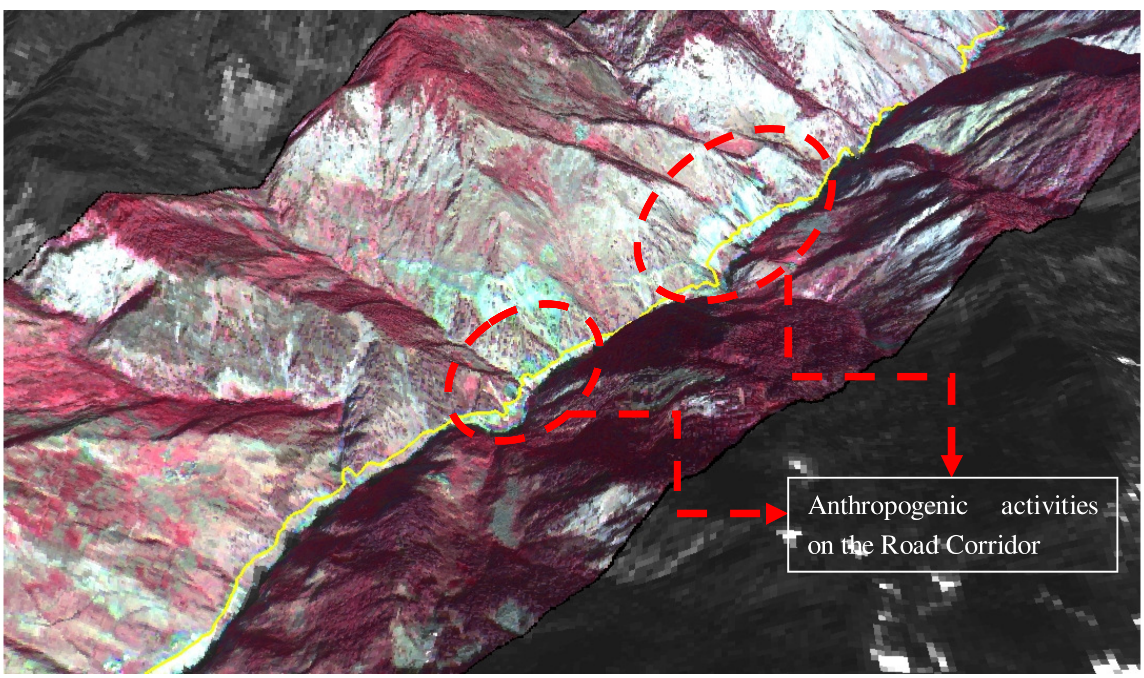

Figure 3-5 showing the anthropogenic activities on the portion of road corridor

3.2.7. Landslides on the Road Corridor

The road corridor is predominantly occupied by numerous small and big landslides above Bhagirathi valley. These slides are mostly occurred due to anthropogenic activities on the road corridor.

Construction and widening of roads along the steep slopes in study area are the main cause of slope instability condition. It was observed that the slides are mostly along the Bhagirathi valley are involves rock and debris fragments which demonstrated a variety of movements. However, the majority of landslides observed were noted to be rock slides and debris slides. Most of them originate in cut slopes, some of them starts from steep slopes and all others are originate in weathered bedrock with several joint sets. Almost all the slides are in south east direction which is same as the gradient and aspect of the study area.

Figure 3-6 showing different landslides zones on different road locations (A) Debris slide near Bhatwari Bridge i.e. 57.5km, (B) Rock Slide in 62.5km and (C) Rock slide near Gangnani Bridge i.e. 67.5 km.

It has also been observed that the landslides occurring in the northern part of the study area generally are rock slides (Fig 3-6, C) due to the steeping slopes of the terrain while the southern part is dominated by debris slides (Fig 3-6, A). The presence of powerful river below the road corridor also cut the basement of the terrain, which leads the land subsidence of the road section. In a road stretch of 11 km length, around 53 landslide events has been recognized during the field survey. Lots of new slope failures have been reported after the Tunnel construction at Thrang in the last rainy season. Due to absence of any other communication like any other road connection or rail network, this Highway becomes the lifeline for this region to join the holy place to the Capital of the State. That is the reason most of the vehicles for Gangotri Pilgrimage got blocked on the way due to the frequent recurrence of the slides in this road corridor.

3.2.8. Geological Setting

The road corridor falls in the southern extreme of the world's youngest tectonic mountain chain; The Himalaya. This mountain chain stretches for about 2500 km from Nanga Parbat (Mountain in English) in Jammu & Kashmir to Namcha Barua in Tibet, with a width of about 250 km (Vaidiya, 1980). According to (Maithani, 1991) the area is constituted by two different group of rocks, which are separated by Main Central Thrust which passes near Sainji i.e. 20km from Uttarkashi along Uttarkashi - Gangotri road. The Garhwal group of rocks are represented by quartzites, epidorites and schistose quartzites while central crystalline group is composed of schists, gneisses, amphibolites and garnetiferous mica-schists etc. The Geological succession is given in the following figure of (Maithani, 1991).

Central Crystalline	Upper Crystalline	--	. Garnetiferous Mica Schists
			. Amphibolites
			. Banded gneisses
			. Augen gneisses
			. Fine grained gneisses
	Middle Crystalline	--	. Streaky migmatites
			. Foliated migmatites
			. Augen migmatites
			. Mylonitic migmatites
	Lower Crystalline	--	. Quartzite muscovite schists
			. Biotite gneisses
			. Quartzite chlorite schist
			. Chlorite schist
Main-------------------------------Central---------------------------Thrust			
	Garhwal Group	--	. Schistose quartzites
			. Quartzites
			. Epidocrites
			. Mylonitic quartzites

Table 3-1 showing the geological succession of Bhatwari and Gangnani Formation (Maithani, 1991)

The Central Crystallines is again sub-divided into three sub-groups i.e. Lower Crystallines, Middle Crystallines and Upper Crystallines. Lower Crystallines constitutes low grade metamorphic rock such as Chlorite schist, Schistose quartzite, Biotite gneiss and mylonitic migmatites separated from Garhwal group by the main Central Thrust (Agrwal, and Kumar, 1973; Purohit, *et al.* 1990).

Middle Crystallines is sandwitched between lower and upper crystallines are varying types of migmatites such as gneissic and banded migmatites and Biotite gneisses with augen gneiss, mica schist and amphibolites etc. Finally northern most Upper Crystallines characterized by phylonite schist with medium to high grade of metamorphism as evidence by the presence of kyanite schist, garnetiferous mica schist and biotite gneiss (Chakraborty, and Anbalagan, 2008).

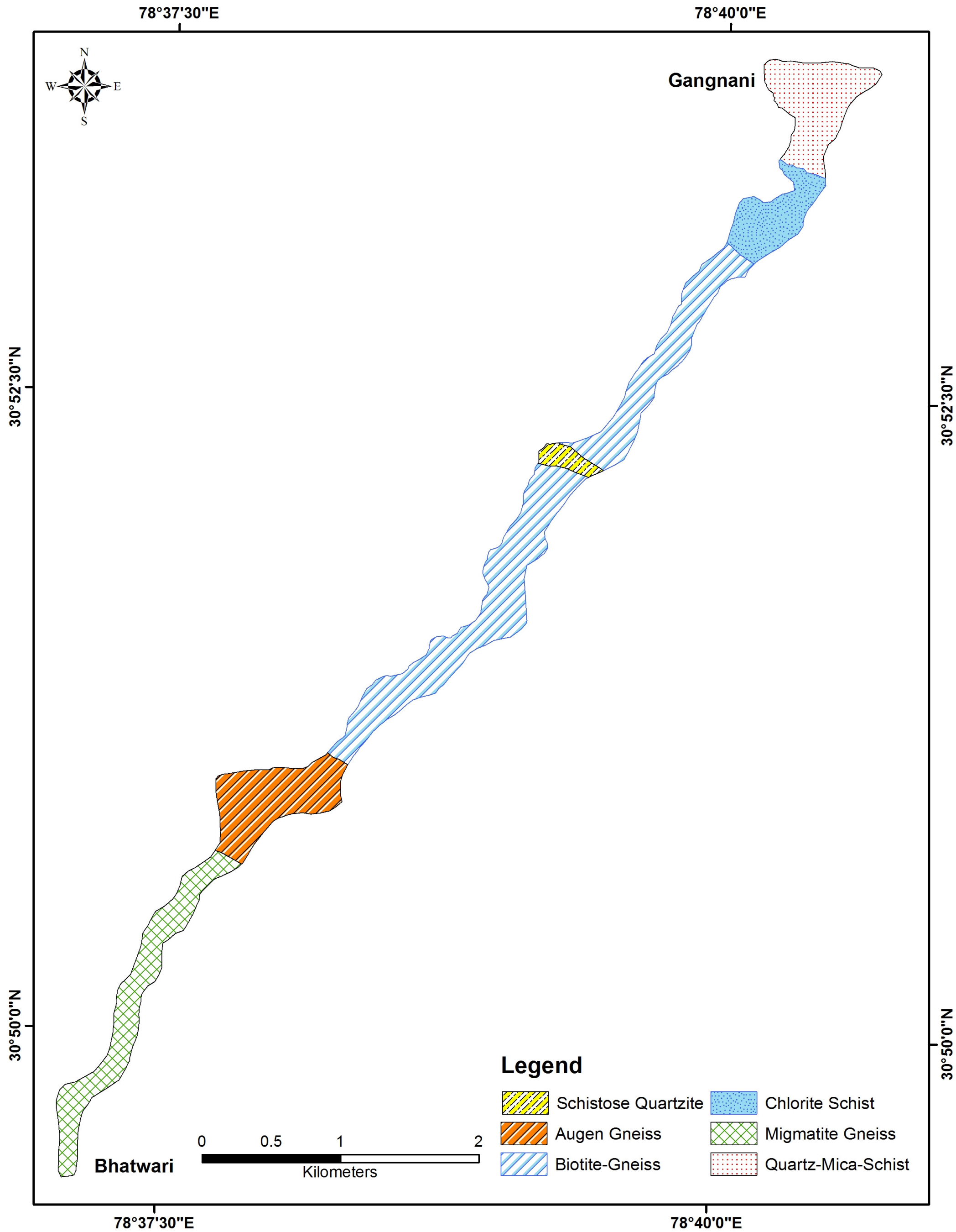

Figure 3-7 showing the Geological map between Bhatwari and Gangnani (Source NRSC)

3.2.9. Traffic density along the road corridor

The selected road corridor is the only communication link for Northern Uttarakhand. This national highway is extended upto Gangotri, which is regarded as one of the holiest place in India and famous for its purity and sanctity. The main festivals occur during the month of August, September and October. Thousands of pilgrims and tourist visit this place during these months. As this highway is only link for Gangotri, traffic density is quite high in the month of August, September and October.

4. Materials and Methods

4.1. Materials

Any kind of scientific research requires materials to be processed to achieve desired result. A landslide risk assessment process requires a lot of material from field as well as satellite imagery for visual interpretation and mapping of landslides for landslide inventory preparation. Details of material required for this project are given in the (Table 4-1).

4.1.1. Data Collection

This section describes the details of data collection during field investigation and from various organization and the processing techniques. Details of data collected during this research are given below in the following (Table 4-1).

Data Types	Source
Satellite Images	National Remote Sensing Centre (NRSC), Hyderabad
Digital Elevation Model	Indian Institute of Remote Sensing (IIRS), Dehradun
Landslide Data	(Chakraborty, 2007; Kuthari, 2007; Sahoo, 2008), Border Road Organization and Field Investigation
Vehicle Information	Toll gate near Bhatwari, Uttarkashi and Field Information
Road damage and cost	Border Road Organization
Local Business details	Field Survey

Table 4-1 showing the details of data types used in this study and sources of these data types

4.1.1.1. Satellite Imagery

For extraction of landslides, satellite imagery and aerial photograph is a basis requirement. Satellite images provide a synoptic view and can also provide different spectral characteristic of landslide rather than other landuse-landcover. In a satellite image the landslide area look very fresh (recent slide) and provide a bright signature which possess particular shape when the image is set in FCC which distinguish the landslide bodies from other landcover units. Stereographic image interpretation of aerial photographs also very useful and appropriate method for demarcation of landslides as it provide the details of boundary of landslides in a 3D view which is possible in satellite images but not as accurate aerial photographs. As aerial photograph is not available for this study area, satellite images are taken for demarcation of landslides in the study area. As many studies are done by many researchers in this area, the satellite images area available in the institute. But all the images are

An available Cartosat DEM was taken from IIRS, Geo-Science Division which was processed on 2009 Cartosat image. Details of satellite images are shown in (Table 4-2).

Satellite	Image Details	Source
Cartosat - IA	Pan 16-Aug-2007	NRSC
	Pan 18-Oct-2008	NRSC
IRS P6	Liss IV 27-April-2007	NRSC
	Liss IV 14-April-2008	NRSC
IRS 1C	Liss III 19-Nov-1998	NRSC
	Pan 11-Oct-1998	NRSC
IRS 1C	Liss III 02-July-2000	NRSC
	PAN 24-Oct-2000	NRSC
IRS 1C	Liss III 22-april-2002	NRSC
	PAN 27-Nov-2002	NRSC
IRS 1D	Liss III 27-June-2004	NRSC
	PAN 10-Nov-2004	NRSC

Table 4-2 showing the details of individual satellite image used in this study

4.1.1.2. Field Data Collection

Landslide risk assessment is a procedure which requires a lot of field investigation. Two field visits was organised, which carries 12 days each during my research in the past 6 months. These field visits are carried out to collect the information on the basis of effect of festive occasion and monsoon on the road corridor.

The 1st field was done to get the primary field data required for the study. During this field investigation we visited Border Road Organisation to cross check the past available landslide record. According to the previous landslide data available some of the landslides are really big in size and shape. A detail geological investigation and public interviews was done by Mr. I.C. Das (Scientist “SE”, Geo-Science Division, IIRS) and me to define the landslide character and intensity. This investigation includes the identification of landslides types, different slope exposures, materials released during a slide and zones of sliding. Various public interviews are also performed to make an analysis on the damaging capacity of the landslides along the road corridor.

A detail field survey for different shops near to road corridor was done for the calculation of indirect risk due to landslides. Data collected for different shops in Gangnani which was located near to the study area. This market is highly affected by landslide events on the road corridor. Data collected on the basis of daily income, daily profit, and effect of daily business for various shops near the road in per hour road blockage for both local and outside visitors.

During 2nd field visit detail traffic information on various types of vehicles i.e. two wheelers, four wheelers and big vehicles were received from the Toll Booth near Bhatwari for last two years and also a weekly counting of vehicles was done for estimation of number of different types of vehicles. Public interviews on road were done for the effect of road blockage due to a landslide for different vehicles. Cost details of road which include repairing cost, maintenance cost and cost for making a new road per kilometre was received from BRO. Also information were collected for the various shops in Harsil and Sukhi top which has important markets and considered as the main food supplying zone for Gangotri and other neighbouring areas. This field visit was done in festive seasons of the study area.

4.1.2. Data Preparation

Data preparation involves checking the quality of collected data for desire accuracy, entering the data into a processing unit, transforming the data and processing it into expected result. The data collected from various organisations and public interviews during field investigation for landslide and related damages are prepared and processed as follows.

4.1.2.1. Demarcation of Study Area

For demarcation of study area, initially it was observed that the landslides are only along the corridor which was due to the unstable steep slopes, so only those areas was considered which have landslides and which can have landslides in future along the road corridor. So, initially a buffer zone of 100 meter to 650 meter buffer zone is made on the right and left side of the road respectively. This zone is demarcated in such a way that all the landslides are in between the area and also the zone which have no landslides but could affect the road as shown in (Fig 4-1).

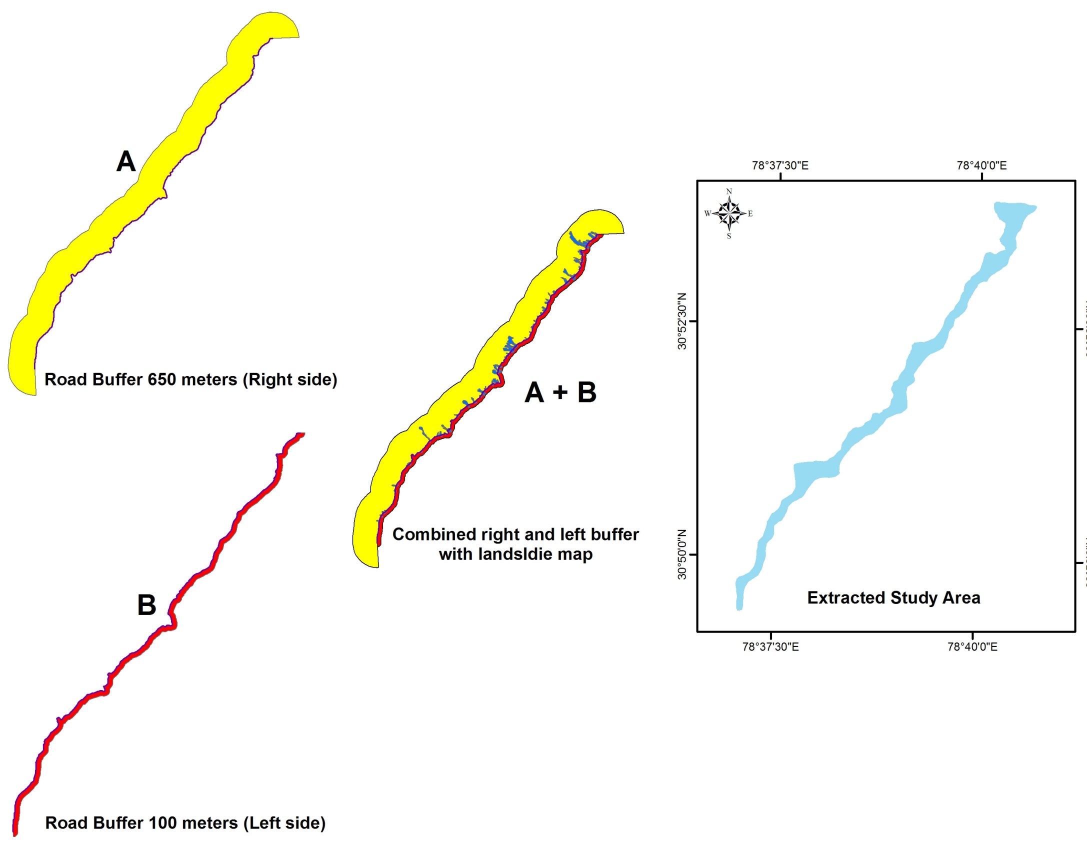

Figure 4-1 showing the procedure for demarcation of study area

4.1.2.2. Geo-referencing and Merging of Satellite Image

For extraction of landslide processed satellite images are the basic need. The satellite images used in this study was also used by previous students who have worked for this particular study area (Sahoo, 2009; Chakraborty, 2008). It is very difficult to manage the previous geo-reference images as they have different projection system, so I prepare my own geo-reference images. All the satellite images as given in (Section 4.1.1.1) are geo-referenced using Erdas Imagine 9.0. For this a reference image was taken from Mr. I.C. Das (Scientist "SE", Geo-Science Division, IIRS). Geo-referencing was done with approximately 0.8 RMSE in polynomial 2nd order. After geo-referencing all the satellite images, resolution merge tool was used for merging the high resolution and low resolution images as shown in (Fig 4-2).

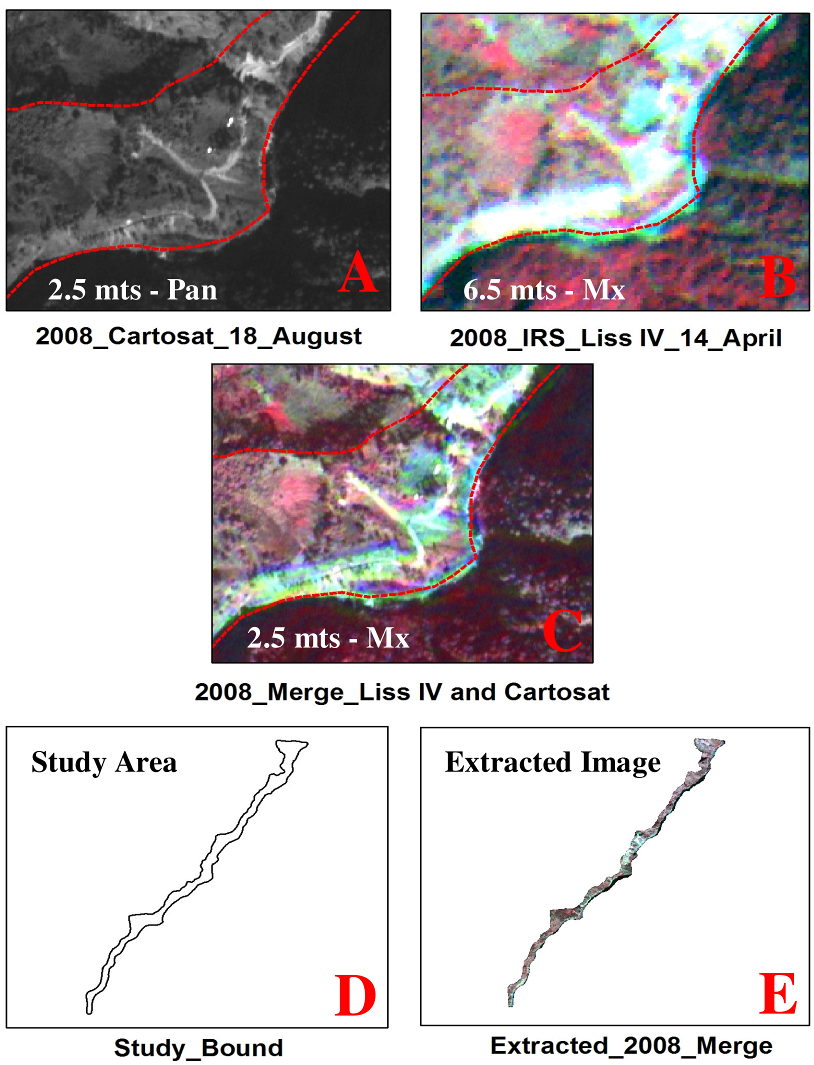

Figure 4-2 showing the geo-referenced image of 2008_Cartosat_18_August (A) and 2008_IRS_Liss IV_14_April (B) and merged image 2008_Merge_Liss IV and Cartosat (C)

4.1.2.3. Geo-environmental Factors

Landslides hazards are highly dependent events. These events are highly dependent on various geo-environmental factors. In this study seven geo-environmental factors are taken for necessity of the study i.e. slope, aspect and drainage as shown in (Fig 4-3). These maps are derived from the National Remote Sensing Centre, Hyderabad.

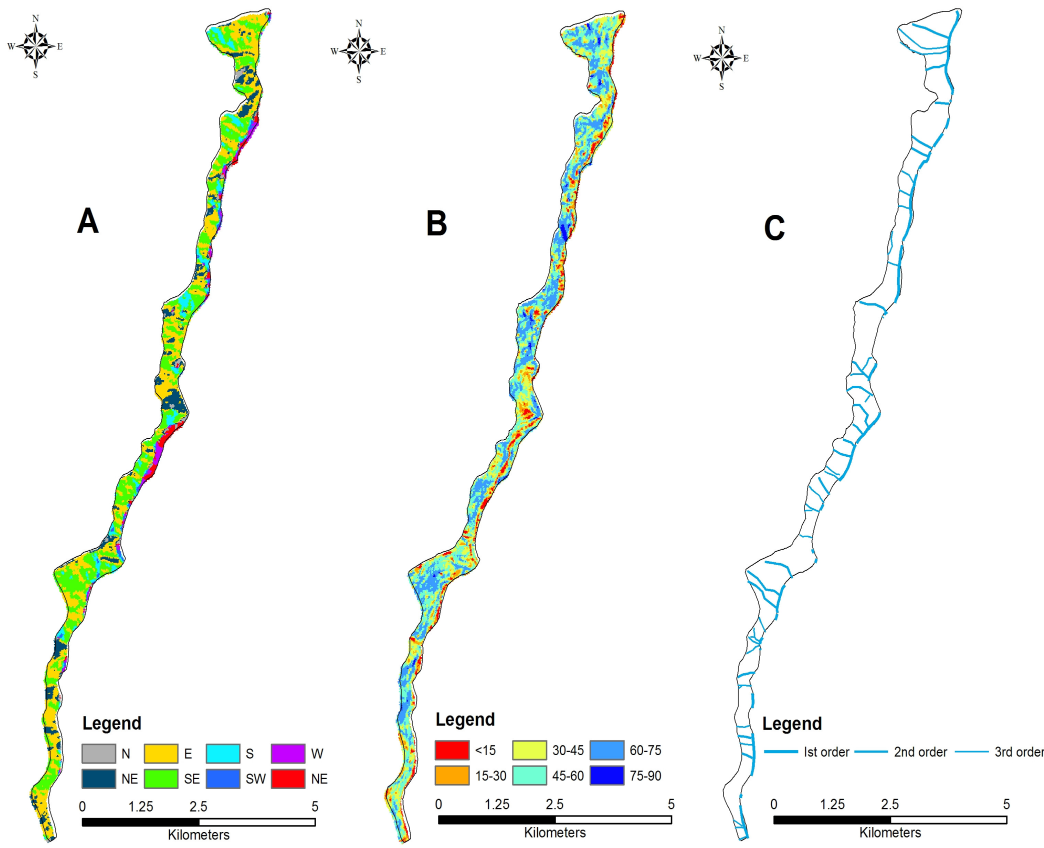

Figure 4-3 showing the Aspect map (A), Slope map (B) and Drainage map (C) for the study area

4.1.2.4. GPS kilometre location

For extraction of landslides from satellite images the road stretch is divided into various sections on the basis of kilometer mark for the road corridor. This kilometre location is obtained during 1st field visit with the help of GPS. The landslide data obtained from BRO is identified by its kilometer location given by BRO officials for their convenience. This kilometer location is correlated with the GPS location taken by us in a GIS environment to obtain the exact location of landslides. The GPS point locations with correlation with BRO kilometer location was given in (Fig 4-4).

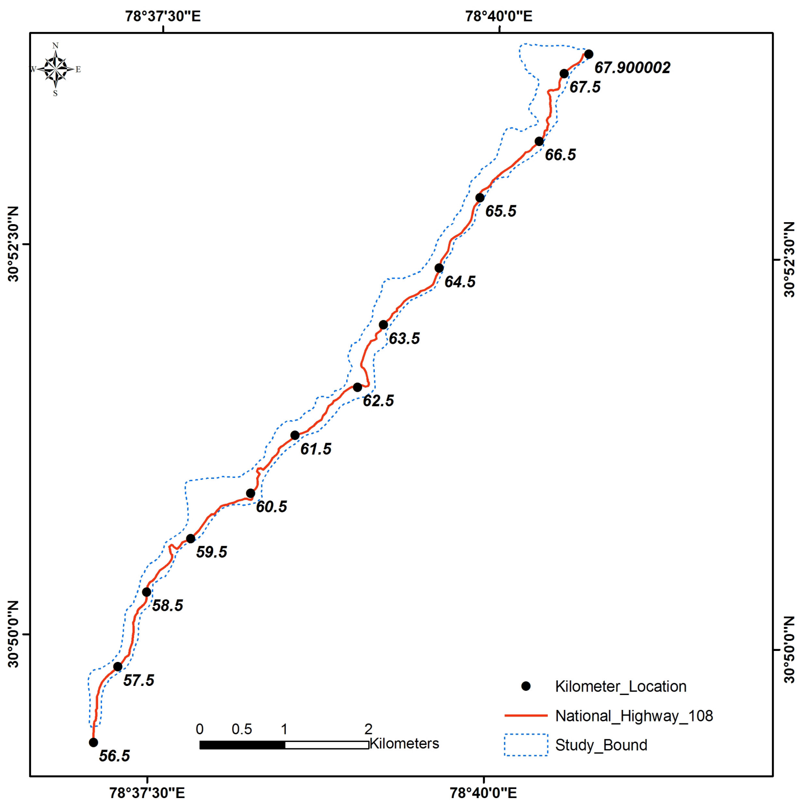

Figure 4-4 showing the GPS locations in different kilometer points for the landslides in the study area

4.1.2.5. Terrain Mapping Units

Mapping units are generated for evaluation of suitability of landslide occurrence in an area on the basis of unique terrain conditions or can be termed as terrain mapping units (TMU) (Guzzetti, *et al.* 2005). TMU refers to those units which have a unique set of terrain characteristics than adjacent or neighbouring units. These are, in principle, homogeneous internally and heterogeneous externally. In landslide studies, they are generated for characterizing the landslide bodies and to facilitate the calculation of spatial probability of landslides. Many researchers have used the concept of TMU for landslides susceptibility analysis; but in various forms like grid cells, slope units, terrain units, unique condition unit, topographic units, landslide units, geo-morphological units and political units (Meijerink, 1988; Cardinali *et al.* 1995; Soeters and van Westen 1996; Pasuto and Soldati 1999; Guzzetti, *et al.* 2005)

In this study area the terrain conditions are quite uneven. High tectonic activities during pre-cambrian age has made the terrain highly steeper and undulating (Fig 3-5). Due to this active tectonic movement the terrain is under continuous deformation which weakens the structural binding of the terrain, triggering slope failures (Barnard *et al.* 2001). This continuous deformation process develops an inhomogeneous condition throughout the terrain which makes the terrain quite difficult for the demarcation of perfect homogeneous units.

The use of mapping units therefore is common in landuse or hazard assessment purposes (Pasuto and Soldati, 1999). They can either be derived automatically from a combination of geo-environmental factors or semi-automatically using expert knowledge based on the requirement and purpose. In present study mapping units were derived semi-automatically on the basis of landslide occurrences and the four geo-environmental factors. This is because of the nature and ruggedness of the terrain that automatic method resulted in numerous homogenous mapping units that did not control the landslides. As a rule of thumb each landslide should be confined to a particular mapping unit. For this mapping units are derived on the basis of landslides occurrences (Pasuto A and Soldati, 1999), slope, lithology, aspect, drainage (Guzzetti *et al*. 2005). These geo-environmental factors are obtained from NRSC. It was observed that almost all the landslides are following the similar trend throughout the terrain. All the landslides are on the individual aspects which directly give a conclusion that all the slope failures are on the individual aspects only. So, all the geo-environmental factors are integrated and carefully all the mapping units are demarcated manually satisfying all the conditions. In this way 120 mapping units were generated in the study area as shown in (Fig 4-5).

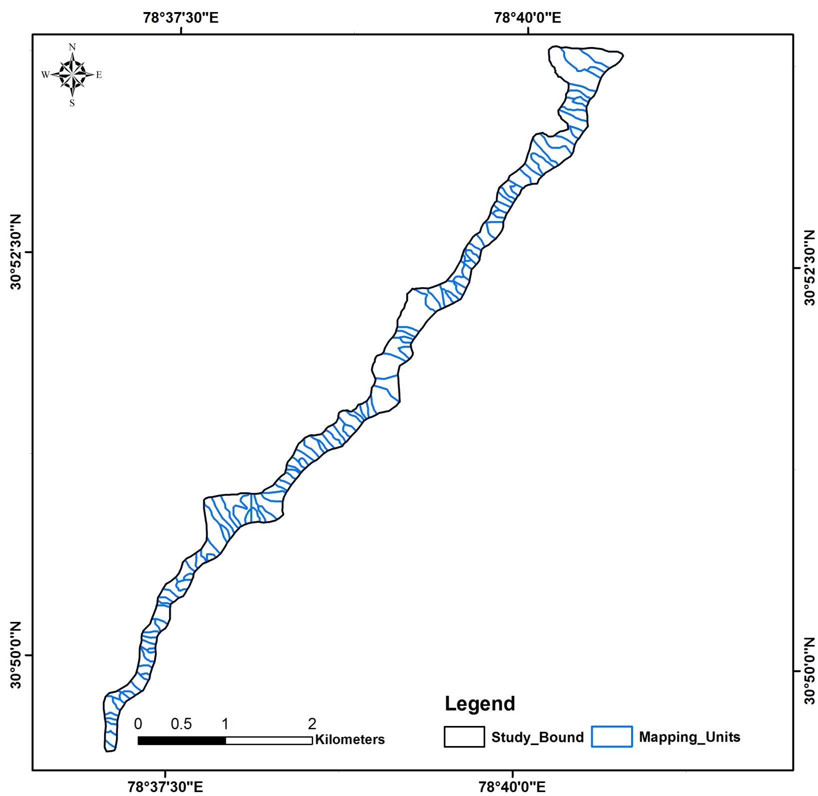

Figure 4-5 showing various mapping units for the road corridor

4.1.2.6. Landslide Data Preparation

The collected field data from various organisation and public interviews are not in a condition for direct processing to achieve expected result. All the collected data are processed as per the requirement of this research. The landslides data are arranged in format of different columns, containing date of occurrence, type, location and amount of material on the road. This arrangement was done for individual landslide types as recorded from BRO register which was shown in (Appendix 1-A and 1-B).

Landslide information obtained from field (Fig 4-6) and public interviews was interpreted properly with experts in IIRS and different conclusions are drawn on the basis of material released, length of the landslide, frequency and its damage done to the road to categorise into different magnitudes for hazard calculation.

Location 59.5 km- Debris slide

Location 57 km- Debris Slide

Location 63.5- Rock slide

Location 64.6- Rock Slide

Figure 4-6 showing different type of landslides in different location of the study area during field survey

4.1.2.7. Landslide Extraction

Landslide map was prepared by extracting the landslides from registered satellite images. Initially GPS point location is taken on the road corridor for measuring the kilometre mark during the field survey. These GPS locations are digitized on the road corridor. On basis of these point locations and prepared landslide data the landslides polygons are digitized on the satellite imagery. This extraction process was done by comparing the kilometre mark of landslides from BRO record and landslide signatures in different years of satellite imagery.

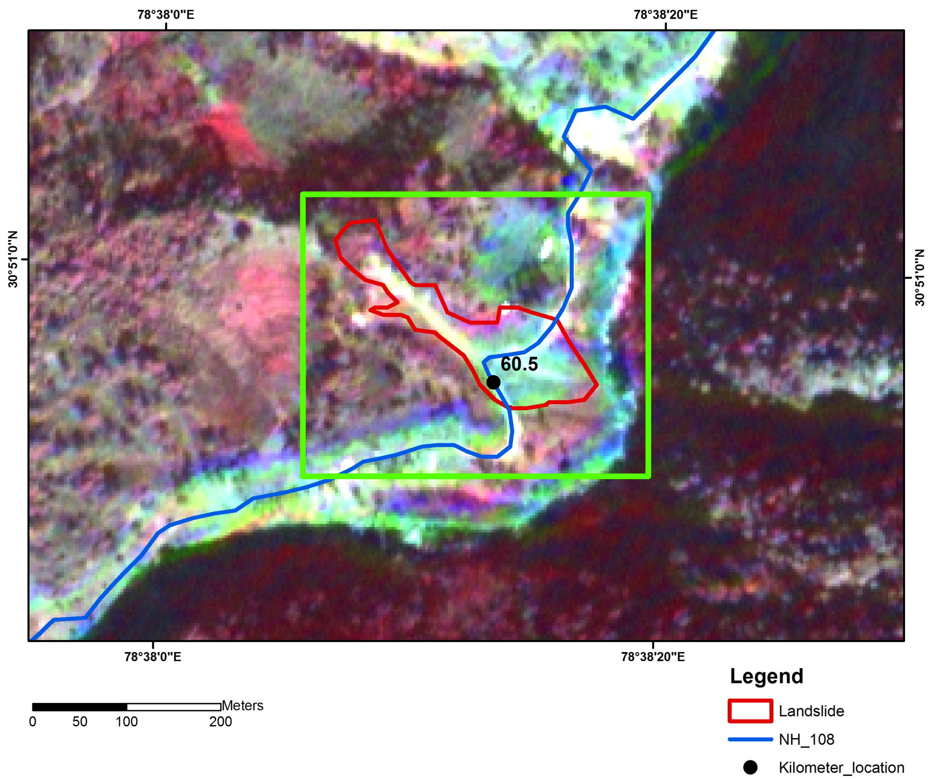

Figure 4-7 showing the extraction of landslides in satellite imagery by identifying the signatures and correlating the GPS point locations with BRO record.

4.1.2.8. Traffic Data Preparation

Traffic information collected for vulnerability calculation from various organizations and field survey was analysed properly. To determine the Average Daily Traffic (ADT) for different type of vehicles on the road a daily chart was prepared by counting the vehicles in both directions and average number of vehicles on the road corridor was obtained by computing the number of vehicles. Counts are done per day, per month and for three month for different type of vehicles passing the selected road corridor. This traffic information has been observed two times in this research, initially data is collected before monsoon on daily basis (i.e. morning, day, evening, night) for one week and same process is done during the monsoon which show change as compared to the pre-monsoon status. Only August, September and October traffic data was taken for the calculation of vehicle density because occurrence of landslides in this road corridor takes place in these three months which is due to monsoon. And as these months are regarded as festive months the traffic density for different vehicles is also very high. Details of ADT from Bhatwari to Gangnani for two wheelers, four wheelers and big vehicles are given in the following (Table 4-3).

Peak Months	Two Wheelers	Four Wheelers	Big Vehicles
Aug	35465	2185	845
September	45764	3760	732
October	40156	3059	788
Sum	121385	9004	2365
ADT	1319.4	97.8	25.7

Table 4-3 showing the Average Daily Traffic for the road corridor

4.1.2.9. Cost of Road

For estimation of cost of road, various data was collected from BRO during the field survey including the cost for making a new road per km, cost for maintenance of a road per km and removing cost of debris per m^3. All the information above was obtained directly from BRO, except the cost of removing the debris which was actually combined from various data. A detail of cost information regarding the road was given in the (Table 5-3) and (Table 5-4).

4.1.2.10. Profit Details

For in-direct loss estimation various shops are interviewed during field survey. It was observed that the shops in Gangnani, Harsil and Sukhi top are the main distributing dealers for the area. So, a details investigation was carried out in terms of daily profit done by a particular type of shop, loss of profit in terms of blockage and no of shops of a particular type. The time taken for this investigation is around 2 weeks. Details of various shops in Gangnani, Harsil and Sukhi top are given (Table 5-11) and (Table 5-12).

4.1.2.11. Software

The use of software in this research was one of the key factors as the software is used as tools in every step of this research. Details of software used in this software are as follows:

i) Arc-GIS 9.2
ii) Erdas Imagine 9.0
iii) R software
iv) Microsoft Office

4.2. Methodology

4.2.1. Landslide Inventory

For any kind of landslide study a correct landslide database is the pre-requisite (Varnes, 1984). Detailed landslide inventory for risk assessment requires mainly the following data inputs: location of landslide, frequency of landslide, causes of landslide and type of landslide etc. (van Westen *et al.* 2006). For the precise landslide identification, accurate landslide mapping and collection of landslide data from reliable sources plays an important role. In India the occurrence of landslides are predominant on the steeper terrains of Himalaya. The major organization which keeps the updated record for landslides in these terrains is Border Road Organization-Uttarkashi (BRO) and Geological survey of India (GSI). The historical landslide records during 1994-2008 of the Border Roads Organization (BRO), India, were highly used in preparing the inventory. Some of the historical landslide records which has been used in this study for generation of landslide inventory is previously obtained by senior researchers (Chakraborty, 2008; Sahoo, 2009) and recent landslides are updated in the study by collection of data from the BRO-Uttarkashi. Multiple satellite images acquired by Cartosat-1, Resourcesat-1, IRS-1C and 1D were also used for deriving morphometric signatures of landslides. In addition extensive field verification was carried out using a GPS survey. Interviewing people residing in the area and visiting professionals working in the area was also a part of the inventory.

For location of landslides a kilometer mark was given starting from 56.5 km to 67.9 km has been given to the National Highway-108 (NH-108) as per the record of BRO-Uttarkashi. To get the kilometre locations more accurate and precise each kilometer is again divided into 100 mts. The demarcation of landslides is done on available satellite images for 1998, 2000, 2002, 2004, 2006, 2007 and 2008 satellite images and these satellite images are also considered for digitization of landslides for alternative years (1994, 1995, 1996, 1997, 1999, 2001, 2003 and 2005) as landslides can be traced upto 3 years from its occurrence.

All the landslide events according to the inventory were mapped at the 1:10,000 scales, which were clearly recognizable from the remote sensing images. Old and inactive ones are included in the inventory of this study as they can activate any time. The old landslides are included because it was observed that some of the portions of the road are sinking due to down cutting action of river along the road in the study area. On the basis of BRO record, degree of slope and field investigation the landslides are categorized into Debris slide and Rock slide (Fig 5-2).

Landslide bodies were mapped from crown to toe of rupture as they are the true susceptible areas leaving aside the run-out zones. These landslides were characterized according to their modes of occurrence. This was done to understand the different geo-environmental factors that control different slope movement types.

4.2.2. Landslide Magnitude

Landslides area or volume can be considered as a proxy for magnitude (Guzzetti *et al.* 2005). Landslides having smaller magnitude possess less threat to the vehicles, people, buildings and roads than the landslides having larger magnitude .The risk from larger magnitude landslides can be

Magnitude Scale	Landslide type	Criteria used to define magnitude	
		Characteristic features	Damages and human Perception
I	Rock Slide	Area < 1000 m^2; Shallow translational; Occurrence on moderate slopes; Shallow slides; run-out distance depend on the slope; initiated from joints and fractures; occurrence probability is high; rapid downhill movement; multiple occurrence; fragmented materials.	Minor damage to the road, vehicles, and infrastructure, can be escaped, controlled by cutting of hanging walls.
II	Rock Slide	Area 1000-10000m^2; deep translational, occurrence on steeper slopes, run-out distance depends on slope, initiated from highly fractured zones, probability of occurrence is more, accumulated on a flat land, single occurrence, material size=2-3m	Major damage to the road, vehicles, and infrastructure, cannot be escaped, controlled using improved stabilization method.
III	Rock Slide	Area > 10000m^2, deep translational occurrence on very high steeper slopes, initiated due to high infiltration of water into bedding or joint planes (weak-zones), occurrence probability is less, single occurrence, material size=8 m.	Full damage to the road, vehicles, infrastructure, difficult to escape, sure death, cannot be controlled.
I	Debris Slide	Area < 1000 m^2; occur in low weathered zones; run out distance = 20m; Shallow translational slides; occurrence probability less;	Only blockage of road; minor damage to the vehicles, infrastructure; easy to escape; controlled by making retaining walls.
II	Debris Slide	Area1000-10000m^2; occur in low vegetation; shallow translational slides; run out distance = 220m; occurrence probability moderate;	Partial damage to the road, vehicles, infrastructure; not so easy to escape; controlled by retaining walls.
III	Debris Slide	Area > 10000m^2; occur in high water content and high weathered zones; deep translational slides; run out distance = 320m; occurrence probability less;	Full damage to the road, vehicles, infrastructure; sure death; cannot be escaped; controlled by spreading wire sheets (Jaiswal *et al.* 2009)

Table 4-4 showing the magnitude separation of different types of landslides on the basis of field investigation and damaging potential

comparatively higher than the smaller magnitude landslide depending upon the proximity of the elements at risk. Due to time constraint a semi-quantitative magnitude classification is done in this study. According to (Jaiswal *et al*. 2009) landslides are divided into different magnitudes on the basis of volume of materials of different slides. The division of different landslides magnitudes is based on the historical landslide record received from BRO, field investigation and available data. The landslides observed in the field and from BRO record show various characteristic. The slides have different characteristic on the basis of type or style of failure, slope amount, run-out distance, frequency of the slide, zone of sliding (i.e. weak-zones in form of joints or fracture), material released due to sliding, human perception on damaging potential of a particular slide. On the basis of above characteristics the landslides record from BRO record and public interviews, it was found that landslides which have higher magnitude (i.e. > 10000m^2) has more damaging record than smaller magnitude landslides which have only covered the road surface with a magnitude <1000m^2. So the data is arranged in a format such that, 3 types of magnitudes is determined by taking the minimum and maximum value and divided it into 3 ranging from Magnitude I (Less Destructive) to Magnitude III (Highly Destructive) depending upon the data.

4.2.3. Landslide Hazard Assessment

A hazard in simple terms can be described as "A natural phenomenon which possesses threat to life, property and infrastructure". Physical scientists defines hazard as the probability of occurrence of a natural phenomenon with a given place and given time (Varnes 1984; Vandine *et al*. 2004). This definition was widely accepted for long period. Later this definition was modified on the basis of magnitude of the natural phenomenon where various researchers proposed that landslide destructiveness depends mostly on magnitude of an event (Hungr 1997). In recent years, (Guzzetti *et al*. 1999) describe a hazard as the "The probability of occurrence of a natural phenomenon in a given place and given time with a given magnitude".

$$H(s,t) = P(s) \times P(t) \times m \qquad \text{(Equation 4-1)}$$

Where;

$P(s)$ = Landslide hazard as the conditional probability of landslide magnitude.

$P(t)$ = Landslide occurrence in an established period.

m = Landslide spatial occurrence

So, in this study landslide hazard assessment is done on the basis of qualitative landslide magnitude classification, landslide type and expected return period. Due to incomplete landslide inventory, magnitude probability is not calculated. So, hazard is expressed as follows:

i) The probability of occurrence of a particular type slide of particular magnitude in an expected time period in a mapping unit.

To obtain this parameter initially the landslide types are classified into different magnitudes on the basis of historical record and field investigation. Then poison probability model is applied for different mapping unit to determine the temporal occurrence of different magnitude type landslides on expected return period and direct method is applied to determine the spatial probability of different magnitude type landslides in each mapping unit. All these maps are finally integrated in GIS environment for hazard estimation. 18 scenarios are generated on the basis of 2 landslide type, 6 landslide magnitudes in 1 yr, 3 yr and 5 yr return periods.

4.2.3.1. Spatial Probability

According to Joint Technical Committee - 1 (JTC-1) spatial probability distribution of an area is highly dependent on two assumptions:

i) The past and present is the key to the future (Varnes, 1984), so the area which have experienced landslide in the past will experience landslide in the future.

ii) Area with similar set of geo-environmental conditions as that of landslide area will experiences landslides in the future.

In general terms the spatial probability is done basically to calculate probability of occurrence of particular type of landslide with a particular magnitude in a particular place. The separation of mapping units on different faces has already done the choice of place of occurrence. The probability for occurrence of landslides in these mapping units is highly dependent on the past landslides occurrences. During inventory preparation a total of 178 landslides events are found in 15 year time period (1994 - 2008) occurring in 96 spatial locations. These 96 spatial locations are not evenly distributed which give rise to some mapping units without landslides. From field investigation and public interviews it was found that these "empty" mapping units have not encountered any landslides in past which directly gives the conclusion for stability of those empty mapping units. In this study the total area is about 2.62 km^2 so the landslides dependent variables i.e. lithology, landuse-landcover and geomorphology have less classes due to small area. Applying indirect methods in this kind of terrain will give almost same weight of landslide occurrence almost through out the terrain which will lead to an erroneous result. So, according to (Guzzetti, 2005) direct method is applied to estimate the spatial probability.

The spatial probability of landslides involves the characterization of type, location and coverage of landslide area. The spatial probability is calculated for each mapping unit, where probability of occurrence of a landslide type with particular magnitude is evaluated in a GIS environment. The overlapping landslide polygons of a particular magnitude are merged to get the total effective area in a mapping unit. Spatial probability of landslides in a mapping unit is estimated by the following equation:

$$P(s) = \frac{A^L}{A^M} \qquad \text{(Equation 4-2)}$$

Where;

$P(s)$ = Spatial Probability of landslide in a mapping unit.
A^L = Area of particular landslide type and particular magnitude in a mapping unit.
A^T = Area of that particular mapping unit.

The spatial probability of landslides is done on the basis of magnitude classification (Table 4-4) and for landslides types. Various scenarios are generated like (i) Debris slide-Magnitude I, (ii) Debris slide-Magnitude II, (iii) Debris slide-Magnitude III, (iv) Rock slide-Magnitude I, (v) Rock slide-Magnitude II and (vi) Rock slide-Magnitude III.

4.2.3.2. Temporal Probability

Landslides occurrences are very much uncertain in nature. Landslides hazard zonation requires both spatial and temporal probability estimation. Especially temporal probability determination involves a huge amount of reliable information on exact dates of occurrence for each slides event on the road corridor. In this study temporal probability is determined by Poisson probability model.

Poisson Probability Model

The Poisson model is a continuous-time model consisting of random-point events that occur independently in ordinary time, which is considered naturally continuous.

Assumptions of the Poisson model

- The numbers of events (landslides) which occur in disjoint time intervals are independent.
- The probability of an event occurring in a very short time interval is proportional to the length of the time interval. The probability of more than one event in such a short time interval is negligible.

The probability distribution of the number of events remains the same for all time intervals of a fixed length. The probability of occurring n number of slides in a time ***t*** is given by

$$P[N(t)] = 1 - [\exp(-\lambda t)] \qquad \text{(Equation 4-3)}$$

Where
N = Total number of landslides occurred during a time *t*
λ = Average rate of occurrence of landslides.
Here time ***t*** is specified, whereas rate ***λ*** is estimated.

The temporal probability calculation is done for individual mapping unit on the basis of individual type and magnitude of landslides, where a value for each unit is counted on the basis of particular magnitude type landslide occurrences for the duration of 15 years (1994 - 2008) from landslide inventory. 36 hazard scenarios are developed on the basis of 2 landslide type and 6 magnitude class in 1yr, 3yr and 5yr return period in each mapping unit. As the record is not enough for the study and incomplete, we have tried to find out the risk in normal conditions using these small return periods.

4.2.4. Vulnerability

Vulnerability is a fundamental component in the evaluation of landslide Risk (Leone *et al.* 1996) which is defined as the level of potential damage, or degree of loss, of a given element (expressed in scale of 0 to 1) subjected to a landslide of given intensity (Fell, 1994; Leone *et al.* 1996; Wong *et al.* 1997). But the main obstacle in the risk assessment is the calculation of the vulnerability for the movable elements at risk and the cost due to the damage of those elements. The vulnerability of static elements can be calculated by making an assessment on the basis of their structure, design, proximity etc (Finlay 1996). But for the movable elements like vehicles, population the assessment of vulnerability needs to have a good historical record for landslide events and related damages (Dai *et al.* 2002).

In this study an effort has been given by referring various literatures to find out the vulnerability value for different road sections and different types of vehicles on the basis of different types of landslides, different magnitudes and return periods. The direct loss calculation is somewhat subjective more difficult to predict because the extent of damage to any element for a particular landslide. But in logical estimation e.g. if the rock slide of magnitude I hits the car, then the vulnerability of the car will be 1. Again if the same volume of debris slide will hit the car then the car has vulnerability < 1. The vulnerability of vehicles mainly depends on the type of vehicles and magnitude of landslide and density of vehicle in a particular time for a particular section of road (Dai, *et al.* 2002).

The risk of any communication route is concerned with the road and vehicles on the road or with any permanent structures along the road corridor. Due to landslide occurrence in every year the permanent structures i.e. buildings and small shops are removed from this road stretch. In this present study the road corridor suffers from serious landslides every year during monsoon. The damage done by the landslides in this route is mostly on the road. Sometimes damage is also observed for vehicles passing on the road as mentioned by public interviews. Various types of data have been collected for the vehicles passing on the road per day. This temporal variability of elements at risk along any road will help to determine the vulnerability by comparing with the density of vehicles on the particular section road.

4.2.4.1. Vehicle Vulnerability

Vulnerability of a vehicle on the road depends on its relative position with respect to a hazard at a specific time (Guzzetti, 2005). Temporal variability of different types of vehicles on the road is determined by dividing the road into different sections on basis of mapping unit. Only those mapping unit are taken which contain landslides. Exact length of the road section is obtained by clipping the mapping unit from total road corridor in Arc-GIS 9.2. The length of the road section was calculated to find out the travel time taken by a vehicle to cross a particular mapping unit on the road. The vehicle speed was taken as 45km/hr, 30km/hr and 20km/hr for two wheeler, four wheeler and big vehicles respectively. For each unit the density of different types of vehicles was estimated on the basis of time taken by a vehicle to cross the mapping unit, average speed of vehicle and ADT. We calculated the expected number of vehicles at any given time on the part of road section as suggested by (Guzzetti, 2005)

$$Nv = \frac{Average\ Daily\ Traffic}{Average\ Speed\ of\ Vehicle} \times Travel\ Time \qquad \text{(Equation 4-4)}$$

where,

N_V = Expected number of vehicles at any time on road section.

Travel time = Time taken by vehicles to travel unit distance on road.

To assess the vulnerability of vehicles in present study a concept was adopted from (Liu, 2006). Similar concept was applied to assess the population vulnerability in this literature where the author obtained the coefficients derived from the relationship between expected population in a particular portion of land at any time and landslide distribution.

$$V(v) = 1 - \exp[(-C) \times Nv] \qquad \text{(Equation 4-5)}$$

where,

C = Coefficient obtained from different type of landslide with relation of expected number of vehicles.

Nv = Expected number of vehicles at a time particular portion of road.

$V(v)$ = Vulnerability value for different types of vehicles for different types of slides and different types of magnitudes in expected return periods.

The method for estimating the vehicle vulnerability was on the basis of Poisson curve which works with average density of vehicles on a particular road section to coefficients of the individual landslide types. For obtaining the coefficients for different vehicles on effect of different landslides, a programme was developed in R software for doing the positive non-linear regression, which was actually done with the help of M Tech student. The data given to software was in the form of absence and presence of individual magnitude type landslides for individual road sections with the vehicle density of different type of vehicles on each road section as proposed by the author of this method.

4.2.4.2. Road Vulnerability

Vulnerability for road is highly depends on the type of slide, magnitude of slide and volume of material on the road. The data obtained from BRO for landslides is highly used in estimating the vulnerability of the road. Details of cost for making a new road, maintenance cost and details of cost for removing the slide materials from the road is also obtained from BRO. Vulnerability of the road for various slide types and different magnitude are obtained by the equation used by (Jaiswal, *et al*. 2009).

$$V(r) = \frac{V(l) \times C(vl) \times L(r) \times R(c)}{C(nr)} \qquad \text{(Equation 4-6)}$$

where;

V(r) = Vulnerability of road for a specific type of slide and particular magnitude in a particular portion of road.
V(l) = Volume of debris on the road in (m^3).
C(vl) = Cost of removing debris ($/$m^3$).
L(r) = Length of the road damaged by particular type and magnitude of slide (km).
R(c) = Repair cost of the damaged road ($/km).
C(nr) = Cost of making a new road ($/km).

4.2.5. Direct Risk Assessment

The impact of landslide directly on the exposed elements like road and any vehicle on the road can be estimated by direct risk assessment. In this study a direct risk assessment is done in the term of economic loss at different locations. The direct risk calculation will be based on the equation below:

$$Sp(e) = H[(s \times t \times m)] \times V(d) \times A \qquad \text{(Equation 4-6)}$$

where,

Sp(e) = Specific risk for different kind of elements at risk.
H[(s,t,m)] = Spatio-temporal occurrence of particular slide and particular magnitude in road section.
V(d) = Vulnerability of different type of elements at risk to a specific landslide.
A = Amount in terms of monetary value of a particular element at risk.

The cost estimation for vehicles, we assumed that all the vehicles are manufactured in India. So, the estimated cost was totally done according to the Indian Standards.

Direct risk assessment in this study was developed for various scenarios on the basis of 6 magnitude classes, 2 landslide types, in particular section in different 1 yr, 3 yr and 5 yr return periods and for two wheeler, four wheeler, big vehicles and road as an element at risk.

4.2.6. In-direct Risk Assessment

Occurrence of landslides on a road corridor not only possesses direct risk to the elements which are in direct contact with the landslides, but also possess in-direct risk to the business in the associated area and to the travellers and tourist on the road. The selected study area is one of the major life-line of northern Uttarakhand which touches Gangotri at the end. Every year during the month of August, September and October, the occurrence of landslides due to monsoon cause high damage to the road and infrastructure and blocks the communication link for numerous tourist making an indirect loss to local peoples and business. Local business in Gangnani, Harsil and Sukhi top which are major station for tourist and local business suffers a lot.

This road corridor is one and only route for this region. In-direct loss due to occurrence of landslide is only by the loss of local business in this route. In this section in-direct risk estimation is done for loss in profit of the local business. In-direct loss is estimated on the basis of time during for a road blockage and profit done by a particular type of shop. The blockage time during an occurrence of landslide is estimated by estimating the time taken for BRO team to reach the landslide site and time taken for removing the slide materials using an excavator. The cost for removing slide materials using an excavator was given in (Table 5-4). Daily profit done by various shops in Gangnani, Harsil and Sukhi top is given in (Table 5-11) and (Table 5-12). In-direct loss for these places due to road blockage is estimated by the equation given by (Jaiswal, *et al.* 2009).

$$IDL = R(d) \times D(p) \times N(s) \qquad \text{(Equation 4-7)}$$

where:

- IDL = In-direct loss due to road blockage.
- $R(b)$ = Road blockage days.
- $D(p)$ = Daily profit done by a particular shop in a day.
- $N(s)$ = Number of shop of a particular type.

Indirect risk assessment was done on the basis of all landslide types, road blockage days, and loss in profit for shops in Gangnani, Harsil and Sukhi top.

5. Results and Discussion

5.1. Analysis of Landslides

A landslide inventory is a record of frequency of landslide occurrences with its location, various types, date of occurrence and its intensity. In this study a multi temporal landslide inventory map was prepared using a 15 year (i.e. 1994 - 2008) historical record from BRO and satellite images of 1998, 2000, 2002, 2004, 2007 and 2008.

The total study area is around 2.65 km^2. The area covered by landslides is about 0.59 km^2 which is 22.3 % of the study area as shown in (Fig 5-1). Among this 22.3 % area of total landslides, the area of rock slides is about 0.5 km^2 (18.52%) while the area of debris slide is about 0.1km^2 (3.7 %) of the study area. The smallest landslide that was mapped from the satellite image and subsequently recognizable in the field had an extent of 144 m^2, while the largest one was 0.052 km^2. The separation of different type of slides was done on the basis of BRO records, field investigation and the steepness of slope obtained from the available DEM. Total distribution of landslides was divided into rock slides and debris slide as shown in (Fig 5-2), where debris flows are also included in debris slides which is due very small in number. It was observed that around 17.2 % of total landslide area is in between 45^0 to 75^0 slope class while other 4.4 % of area of landslides is in between 0^0 to 45^0 which mainly separates the landslides into rock slides and debris slides (Fig 5-1) and (Fig 5-2). The higher number of rock slides in the terrain is due to the geological condition prevailing in the terrain, which forms a continuous deformation of structures in the terrain and resulting steep slopes throughout the terrain and large number of road cuts in weathered and fractured rock. This highly steeping zone with combination of hard rock type lithology and various anthropogenic activities with rainfall have given a high chance to trigger slope failures in form of rock slides.

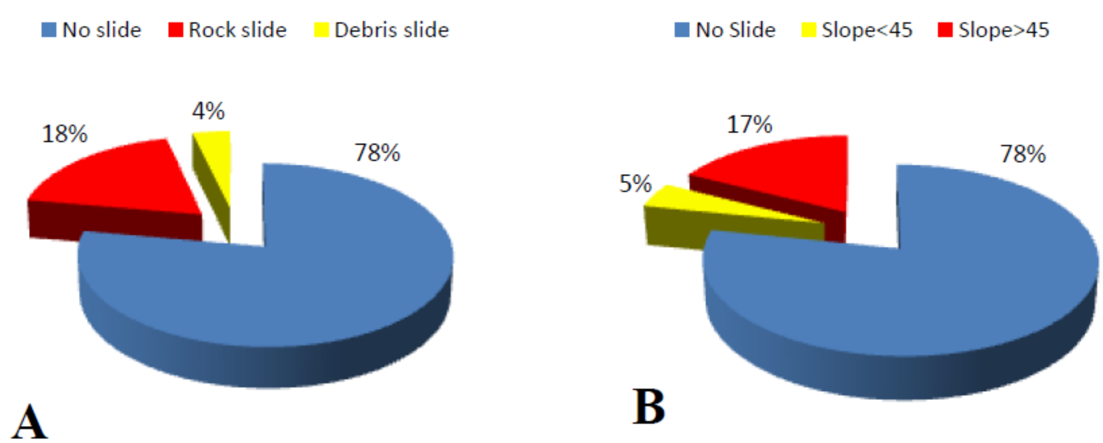

Figure 5-1 showing the percentage of type of landslide in total study area (A) and percentage of slide in different slope unit (B).

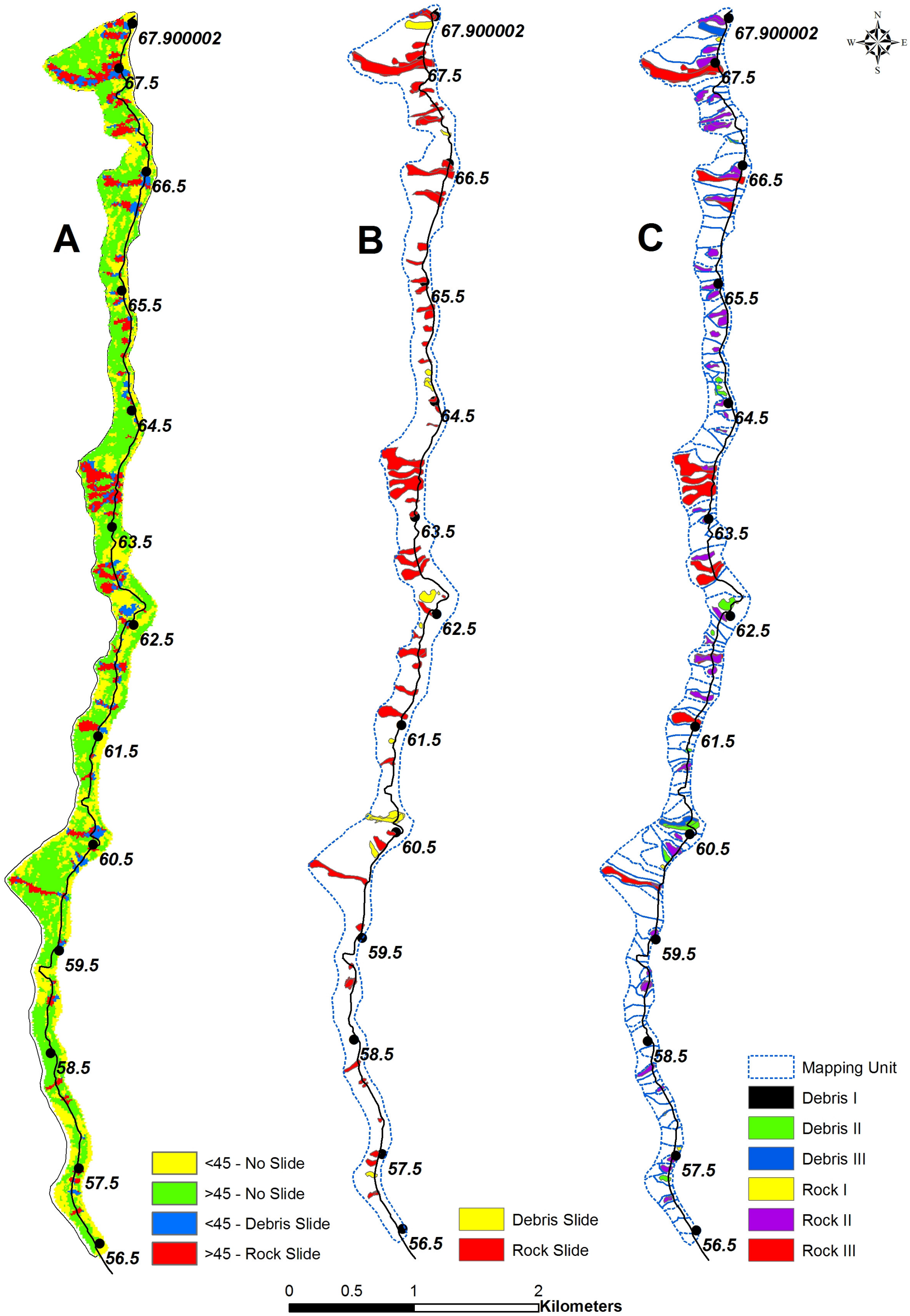

Figure 5-2 showing the different landslides in different slope units (A), landslide inventory map (B) and landslides of different magnitude (C)

The total number of landslides occurrences is 178 during 1994 to 2008. The maximum no of landslide occurrence was found in the years 1994, 1998 and 2008 in which, 1994 is having maximum of 60 slides in the road stretch where as 1999, 2001 and 2005 are not having landslides (Fig 5-2 and Fig 5-3). The maximum number of occurrences belongs to rock slides as discussed earlier (Fig 5-1), occurring in 140 different locations from 1994 to 2008 at 67 different spatial locations where as number of debris slides are very less around 38 events in 11 spatial locations (Fig 5-4). The landslides affecting the area are mainly shallow translational rock slides and debris slides which was investigated during field survey.

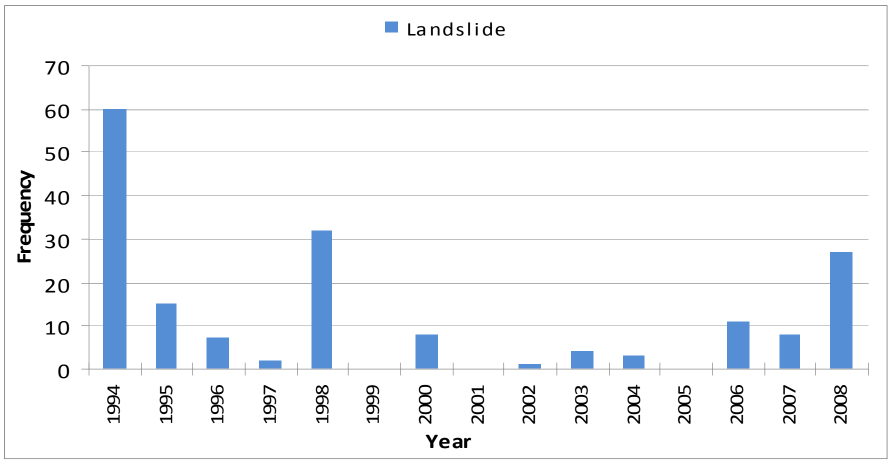

Figure 5-3 showing the occurrence of landslide from 1994 to 2008

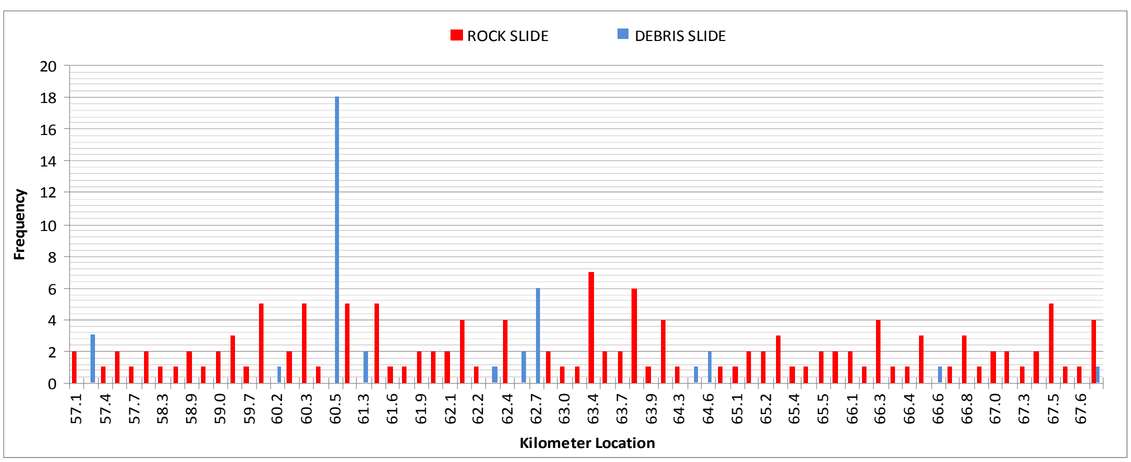

Figure 5-4 showing the landslide distribution on stretches of 200 meters for different kilometer location

The highest frequency of debris slides is 18 in the 60.5 kilometer location and the lowest frequency of debris slide is found to be 1 in 5 different locations throughout the road stretch (Fig 5-4). The highest number of debris slides in kilometer 60.5 is because of the anthropogenic activities done for widening of road and stabilizing the slope (Fig 3-5). Highest frequency of rock slides is found to be 7, observed in kilometer 63.4 location and the lowest frequency is found to be 1 in various locations of the road stretch (Fig 5-4). The northern portion of road stretch has the highest density of rock slides as compared to the southern part which has very less debris slides. This higher density of rock slides is due to the steepness of the highly fractured terrain in the northern part. The highest length of landslides was found for rock slides of 465 meters and smallest of 19 meters whereas highest length for debris slides is 325 meters and smallest is 31 meters.

The distribution of landslides in various road stretches is not even. It was observed that from 120 mapping units 68 units have no slides and in the remaining 52 mapping units only 10 units have debris slide and other 40 units have rock slides in which the occurrence of both debris slide and rock slide was found in 2 units i.e. 84 and 72nd unit (Fig 5-5). Absence of occurrence of landslide in different years and in different mapping units justify that landslides are temporally discrete and spatially random events which are very difficult to predict.

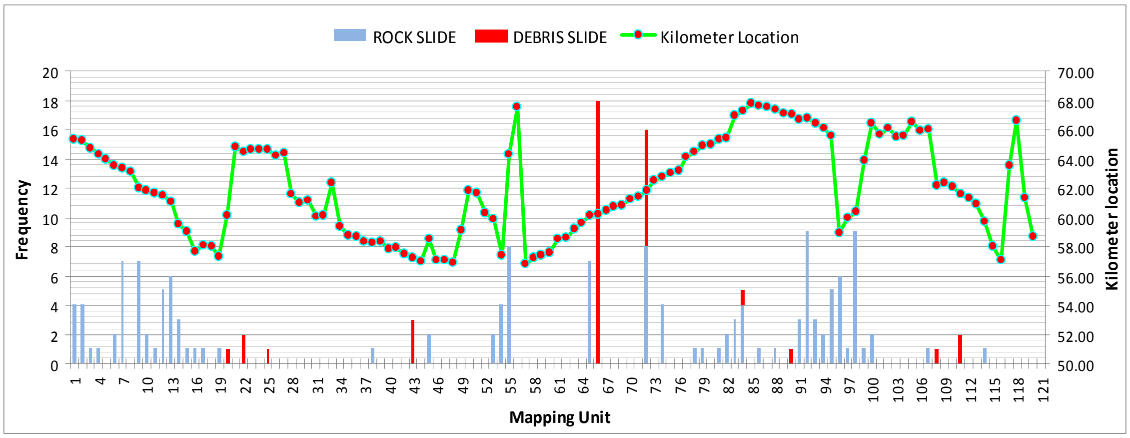

Figure 5-5 showing the relation between the frequency and kilometer location of landslides in different mapping unit

Landslides vary in size, and were classified into various magnitudes based on their size. Depending on the size of the landslides they are classified into various magnitudes. In this study landslides area divided into 3 magnitude class for rock and debris slide on the basis of area derived during extraction of landslide from satellite image and field investigation as described in (Section 4.1.2.7). This extraction was also done by (Sahoo, 2009) for landslide susceptibility using SSPC, he derived the landslides form Cartosat image for year 2008 and 2007 and only found 76 slides for these two years. The main objective of his research was to compare the relation between the results susceptibility from logistic regression and SSPC model, so majority of work was done analysis of slope faces and different geo-environmental factors. A temporal hazard scenario was developed using an inventory of 5 years by (Chakraborty, 2008), which was for bigger stretch than this study area, and found out more than 200 landslides. Landslides of 2007 and 2008 are easily identified in the satellite imagery as well as in field but landslides which are not identified in the field (i.e. from 1994 to 2006) and are traced by matching the signatures on a satellite imagery and historical record obtained from BRO. In this study, the area of landslides varies differently according to the magnitudes and type of landslides. Rock slide of magnitude I, II and III covers 13%, 31% and 36% of the total landslide area respectively in this study while debris slide of magnitude III covers 11% of the study area and magnitude II and I cover 6% and 3% respectively of the total landslides (Fig 5-6). Area of rock slide is the higher than the area of debris slide is because of more no of occurrence of rock slide in the study area.

The distribution of landslide magnitudes of rock slides and debris slide in various mapping unit reveals that, the occurrence of Debris I is very low, occurring only in 72nd unit while the occurrence of Rock II is dominant throughout the terrain occurring in almost 41 mapping units (Fig 5-8), which is due to higher occurrence of rock slide through out the terrain as discussed earlier. The highest number of occurrence is found for Debris II on the 66th unit (Fig 5-8) while the lowest number of occurrence is 1 for both rock and debris slides. Rock III is having highest frequency of 8 for 55th unit. It was also observed that landslide of four different magnitude of landslides are found in 72nd unit (Fig 5-8).

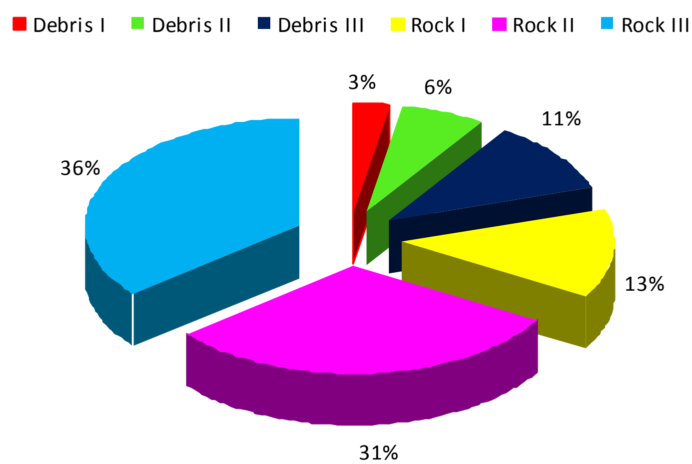

Figure 5-6 showing the area of different magnitude type landslide

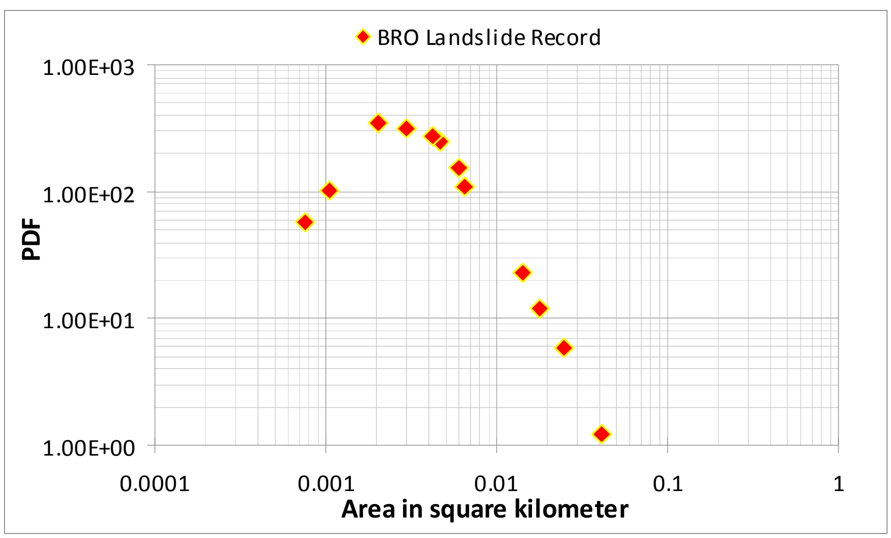

Figure 5-7 showing the dependency of landslide area on probability density function (PDF)

The distribution of all the landslide areas with the probability density function (Fig 5-7) shows the incompleteness of the inventory, due to lack of smaller landslides which was not recorded in BRO. The incompleteness of the inventory was also because this inventory was only for 15years. The present inventory in this study was considered partially complete. It was analysed that all the area of landslides in this multi temporal inventory have a good correlation with the power law scaling exponent, where the smaller landslides are following the exponential rollover and bigger landslides are showing the power law decay tail in this probability density model as (Malamud, *et al.* 2003).

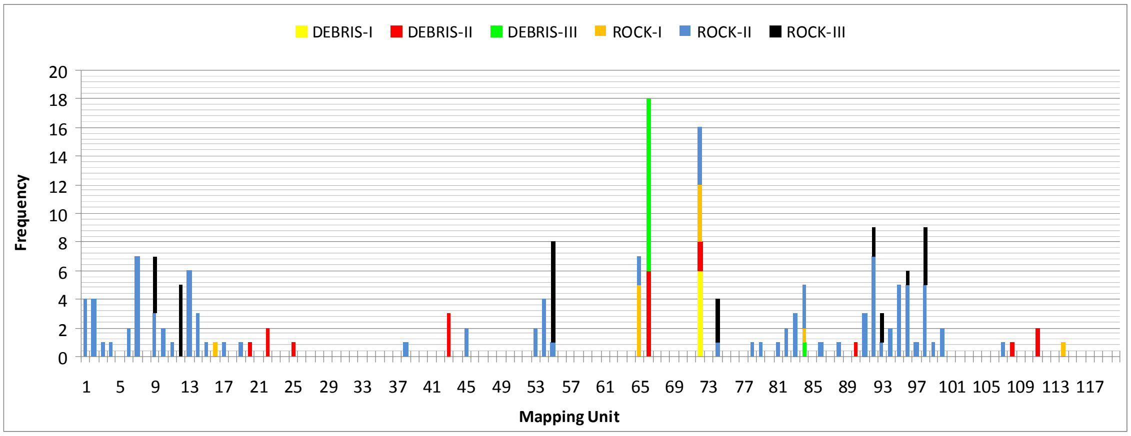

Figure 5-8 showing occurrences of different magnitudes of rock and debris slides types in different mapping units

5.2. Spatial probability

Spatial probability determines the location where the occurrences of landslides are frequent. Spatial probability of landslides in this study is calculated on the basis of area of the landslides of different types and magnitude with respect to the area of the mapping unit as described in (Section 4.2.4.1). For this only those mapping units are taken which have landslides in it. A total of 53 mapping units are considered which have debris and rock slide with all magnitudes.

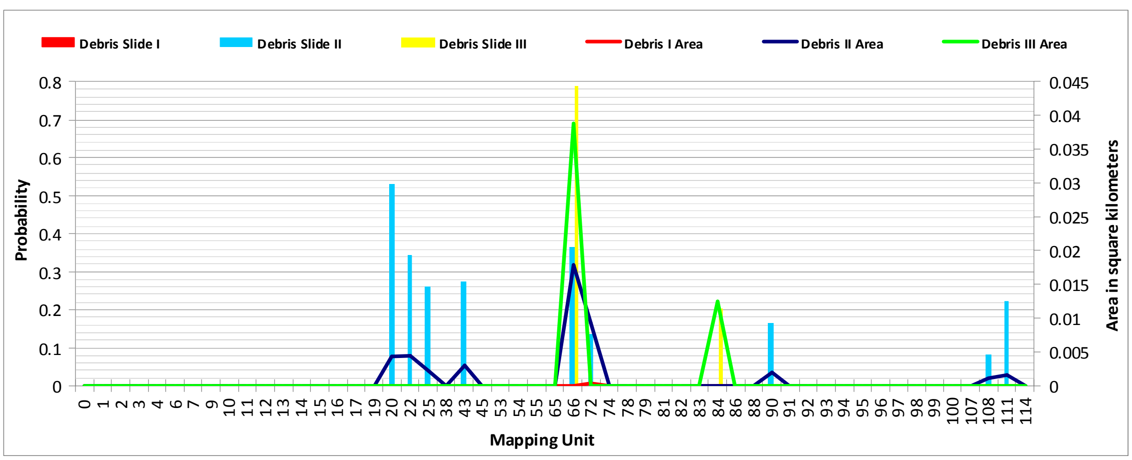

Figure 5-9 showing the spatial probability of Debris slide magnitude I, Debris slide magnitude II and Debris slide magnitude III

As shown in the (Fig 5-9) the occurrence of debris slide I is only in the 72nd unit of the study area. Due to the small area of landslide of this particular magnitude type i.e. 0.00035km^2, w.r.t to the area of mapping unit, the probability of occurrence for this particular magnitude type landslide is very less in this particular unit. Debris slide magnitude II is having 9 different spatial locations as shown in (Fig 5-9). The area of landslide in 66th unit is the maximum for this type i.e. 0.018km^2 but shows less probability because of the bigger area of the corresponding mapping unit. While other landslides in 20th unit shows higher probability of occurrence which is due to the small area of the mapping unit. The lowest occurrence of landslide is shown in 90th unit of the study area i.e. 0.16. In case of debris slide magnitude III the landslides are occurring in two spatial locations i.e. 66th and 84th unit (Fig 5-9).The probability of occurrence of debris slide magnitude III is having a well distributed pattern as shown in (Fig 5-9) where the bigger landslides is having higher probability of occurrence and smaller landslides are having lower probability. The increase in probability of occurrence of landslides in this case is due to the area of mapping unit, which is comparatively low w.r.t landslide area but high in the other debris slide magnitudes. The biggest landslide in this type is about 0.038km^2 and probability is 0.8 in 66th unit, while the area of smallest landslide is 0.014km^2 and probability of occurrence is 0.2 in 84th unit (Fig 5-9).

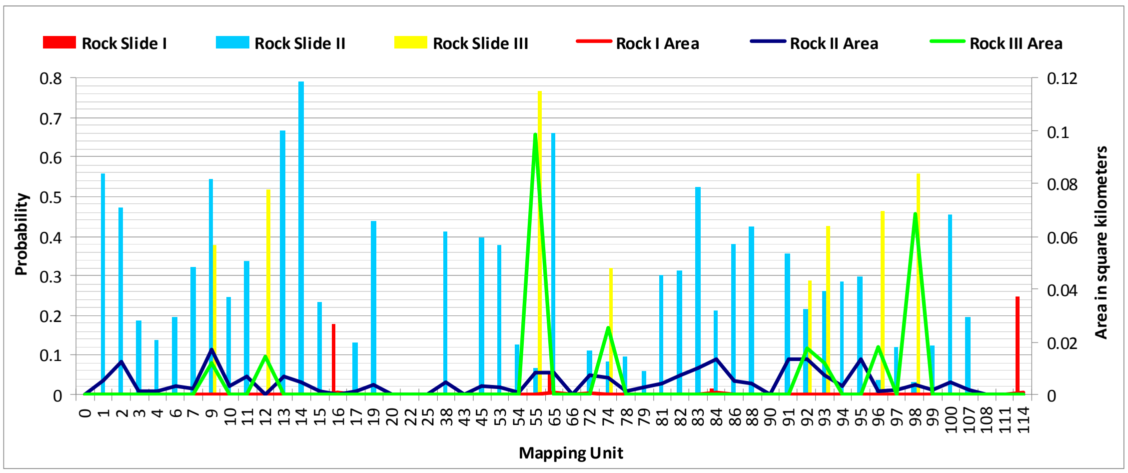

Figure 5-10 showing the spatial probability of Rock slide magnitude I, Rock slide magnitude II and Rock slide magnitude III

The occurrence of rock slide magnitude I is in 5 spatial location where the highest area of rock slide is found to be in 16th, 84th and 114th unit of the study area i.e. 0.0009km^2 approximately, but the highest probability of occurrence of landslides is only found in 114th unit i.e. 0.009 as shown in (Fig 5-10). In the 84th unit of the study area the area landslides is bigger but the area of the mapping unit is comparatively much more than the area of the landslides due to which the probability of occurrence of landslide is low in this unit. The lowest probability of rock slide is found to be in 72nd unit of the study area i.e.0.0001 (Fig 5-10). The spatial distribution of rock slide magnitude II is high in the study area, occurring in about 41 spatial locations (Fig 5-10). The larger area of landslide of this type is in 9th unit of the study area i.e. 0.017km^2 and highest probability was found to be in the 14th unit i.e. 0.78 (Fig 5-10). The smallest area was found to be in 54th unit i.e. 0.001km^2 and lowest probability was found to be in 96th unit i.e. 0.04. Some units like 9, 91, 92 and 95th are having low probability of occurrence but the area of these landslides are high which directly indicate that the area of the mapping unit is very much bigger than the landslide area. The rock slide magnitude III in this study is occurring in 8 different spatial locations (Fig 5-10). In this case the biggest landslide was found in 55th unit i.e. 0.1km^2 having the highest probability of 0.78. The smallest landslide is found to be in 9th and 93rd unit i.e. 0.01km^2, where the probability of occurrence is quite high because of the small area of the mapping unit. In unit 98 the area of the landslides is bigger as compared the other unit except unit 55 i.e. 0.07km^2, with an probability of 0.56, which is quite high as compared to other units in this study. The higher probability in this unit is also due to the smaller area of the mapping unit.

5.3. Temporal probability

Temporal probability is estimated in this by using Poisson probability model. This is done basically on the basis of the number of occurrence of a landslide in a particular mapping unit which is estimated on the basis of different magnitude type landslides in 1yr, 3yr and 5yr return period as discussed in (Section 4.2.4.2). The estimation of temporal probability was done for small return periods because it was observed that by taking bigger return periods like 10yr and 15yr the probability of occurrence of landslide is 1 for maximum landslides in this study which can give erroneous result, so in this study the temporal probability was estimated on small return periods.

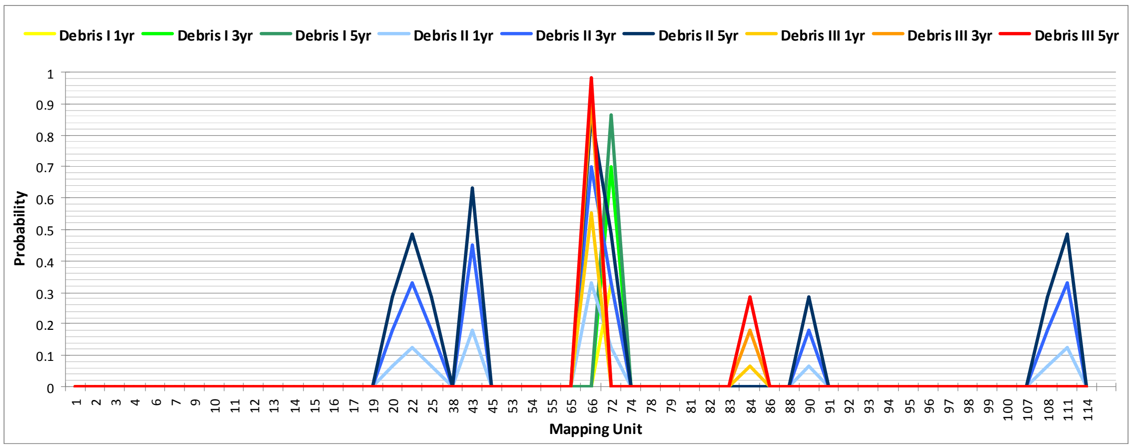

Figure 5-11showing the temporal probability of Debris slide magnitude I, II and III for 1yr, 3yr and 5yr return period

As shown in the (Fig 5-11), debris slide magnitude I is in the 72nd unit of the study area. The occurrence of this particular type landslide is about 6 times during 15 years from 1994 to 2008 (Fig 5-8). The temporal probability of this particular type of landslides in 1yr, 3 yr and 5yr return period are given in (Fig 5-11), where the 5yr return period is having the highest probability of occurrence i.e. 0.87 as estimated from Poisson Probability Model. The temporal probability of debris slide magnitude II shown in (Fig 5-11) is having 9 spatial locations where the highest frequency of landslide is located in 66th unit of the study area (Fig 5-8). The lowest frequency of this type of landslides is located in 4 units (i.e. 20, 25, 90 and 108th unit) which also have the same temporal occurrence in 1yr, 3yr and 5yr return period. Debris slide magnitude III is having the two spatial locations in 66th and 84th unit of the study area (Fig 5-8). The landslide in the 66th unit of the study area is having the highest frequency (i.e. 12 times) because of the blasting operations performed for this road corridor weakens the terrain causing slope failures frequently in this particular section of road. It was difficult to analyse the temporal probability of landslide in these situations (blasting operations), but it was observed that these blasting operations only weakens the terrain where slope failures initiates was recorded only during the monsoon as like other landslide occurrences in the terrain. Due to the higher frequency the temporal probability of debris slide III is also higher i.e. 0.6 in 1yr and 0.9 in 5 yr return period.

The temporal occurrence of rock slide magnitude I was found in 5 different locations in various frequencies (Fig 5-12). The highest number of occurrences of these slides is found to be in 65th unit of the study area i.e. 5 times (Fig 5-8) occurring with a temporal probability of 0.3 in 1yr and 0.8 in 5yr

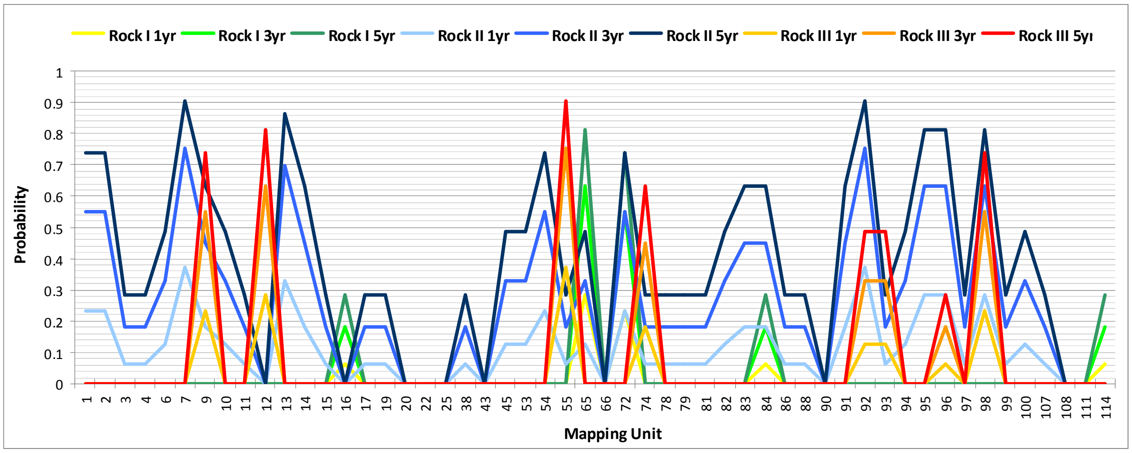

Figure 5-12 showing the temporal probability of Rock slide magnitude I, II and III for 1yr, 3yr and 5yr return period

return period (Fig 5-12). The lowest of all frequency for these slides was found to be 1 in 15 years occurring in 16, 84 and 114th unit of the study area. The low frequency indicates the stabilization of slopes which reduces the occurrences of rock slides in the study area from 1994 to 2008. Rock slides magnitude II is having the higher number of landslides in this study. Slides of this type occupy almost all the units of the study area. The occurrence of rock slide II in found to be in 41 units of the study area leaving only 9 units (Fig 5-12). The highest number of rock slides II in the study is because of the highly fractured steeper rocky terrain present along the road corridor where the un-stability generates due the precipitation in the fissures like joint, bedding, fractures or discontinuity in the terrain. The highest number of rock slide was found to be in 7th and 92nd unit where the temporal probability was 0.9 in 5yr return period (Fig 5-12). The rock slides of magnitude III are found in 8 units. These are most catastrophic events occurred very less as compared to other magnitudes of landslides in the study area. The highest number of these kinds of landslides is found to be in 55th unit of the study area occurring with a temporal probability of 0.9 in 5yr return period and lowest in 96th unit having a temporal probability of 0.3 in 5yr return period (Fig 5-12).

5.4. Landslide Hazard Analysis

Landslide hazard assessment is basically the product of spatial probability and temporal probability of different landslide types and magnitudes. In this study the spatial probability obtained from the area (Section 5.2) of landslides and temporal probability estimated from frequency (Section 5.3) of landslides during 15 years was multiplied on the basis of different magnitude classes and individual return periods. A total of 18 hazard scenarios are developed in this study by using 2 types of landslide, 3 magnitude class of each landslides type occurring in 1yr, 3yr and 5yr different return periods as discussed in (Section 4.2.3).

The hazard for debris slide magnitude I is having in only one unit i.e. 72 unit of the study area. The probability of occurrence of this category of landslide in very low i.e. 0.0045 in 5 yr return period and 0.002 in 1yr return period (Table 5-1). It was observed that the temporal probability of this particular landslide is quite high as shown in (Fig 5-11) i.e. occurring 6 times in 15 years from 1994 to 2008 with a probability of 0.8 in 5yr return period, but the spatial probability of this landslide is quite

Mapping	Debris Slide I			Debris Slide II			Debris Slide III			Rock Slide I			Rock Slide II			Rock Slide III		
Units	1yr	3yr	5yr	1yr	3yr	5yr	1yr	3yr	5yr	1yr	3yr	5yr	1yr	3yr	5yr	1yr	3yr	5yr
1	0	0	0	0	0	0	0	0	0	0	0	0	0.13	0.31	0.41	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0.11	0.26	0.35	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0.01	0.03	0.05	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0	0.01	0.02	0.04	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0	0.02	0.06	0.10	0	0	0
7	0	0	0	0	0	0	0	0	0	0	0	0	0.12	0.24	0.29	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0	0	0.10	0.25	0.34	0.09	0.21	0.28
10	0	0	0	0	0	0	0	0	0	0	0	0	0.03	0.08	0.12	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0	0	0.02	0.06	0.10	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.15	0.33	0.42
13	0	0	0	0	0	0	0	0	0	0	0	0	0.22	0.46	0.57	0	0	0
14	0	0	0	0	0	0	0	0	0	0	0	0	0.14	0.36	0.50	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0	0	0.02	0.04	0.07	0	0	0
16	0	0	0	0	0	0	0	0	0	0.01	0.03	0.05	0	0	0	0	0	0
17	0	0	0	0	0	0	0	0	0	0	0	0	0.01	0.02	0.04	0	0	0
19	0	0	0	0	0	0	0	0	0	0	0	0	0.03	0.08	0.12	0	0	0
20	0	0	0	0.03	0.10	0.15	0	0	0	0	0	0	0	0	0	0	0	0
22	0	0	0	0.04	0.11	0.17	0	0	0	0	0	0	0	0	0	0	0	0
25	0	0	0	0.02	0.05	0.07	0	0	0	0	0	0	0	0	0	0	0	0
38	0	0	0	0	0	0	0	0	0	0	0	0	0.03	0.07	0.12	0	0	0
43	0	0	0	0.05	0.12	0.17	0	0	0	0	0	0	0	0	0	0	0	0
45	0	0	0	0	0	0	0	0	0	0	0	0	0.05	0.13	0.19	0	0	0
53	0	0	0	0	0	0	0	0	0	0	0	0	0.05	0.12	0.18	0	0	0
54	0	0	0	0	0	0	0	0	0	0	0	0	0.03	0.07	0.09	0	0	0
55	0	0	0	0	0	0	0	0	0	0	0	0	0.00	0.01	0.02	0.29	0.58	0.69
65	0	0	0	0	0	0	0	0	0	0.02	0.04	0.05	0.08	0.22	0.32	0	0	0
66	0	0	0	0.12	0.26	0.32	0.43	0.72	0.77	0	0	0	0	0	0	0	0	0
72	0.00	0.00	0.00	0.02	0.05	0.07	0	0	0	0.00	0.00	0.00	0.03	0.06	0.08	0	0	0
74	0	0	0	0	0	0	0	0	0	0	0	0	0.01	0.01	0.02	0.06	0.14	0.20
78	0	0	0	0	0	0	0	0	0	0	0	0	0.01	0.02	0.03	0	0	0
79	0	0	0	0	0	0	0	0	0	0	0	0	0.00	0.01	0.02	0	0	0
81	0	0	0	0	0	0	0	0	0	0	0	0	0.02	0.05	0.08	0	0	0
82	0	0	0	0	0	0	0	0	0	0	0	0	0.04	0.10	0.15	0	0	0
83	0	0	0	0	0	0	0	0	0	0	0	0	0.09	0.24	0.33	0	0	0
84	0	0	0	0	0	0	0.01	0.04	0.06	0.00	0.00	0.00	0.04	0.10	0.13	0	0	0
86	0	0	0	0	0	0	0	0	0	0	0	0	0.02	0.07	0.11	0	0	0
88	0	0	0	0	0	0	0	0	0	0	0	0	0.03	0.08	0.12	0	0	0
90	0	0	0	0.01	0.03	0.05	0	0	0	0	0	0	0	0	0	0	0	0
91	0	0	0	0	0	0	0	0	0	0	0	0	0.06	0.16	0.22	0	0	0
92	0	0	0	0	0	0	0	0	0	0	0	0	0.08	0.16	0.19	0.04	0.09	0.14
93	0	0	0	0	0	0	0	0	0	0	0	0	0.02	0.05	0.07	0.05	0.14	0.21
94	0	0	0	0	0	0	0	0	0	0	0	0	0.04	0.09	0.14	0	0	0
95	0	0	0	0	0	0	0	0	0	0	0	0	0.08	0.19	0.24	0	0	0
96	0	0	0	0	0	0	0	0	0	0	0	0	0.01	0.02	0.03	0.03	0.08	0.13
97	0	0	0	0	0	0	0	0	0	0	0	0	0.01	0.02	0.03	0	0	0
98	0	0	0	0	0	0	0	0	0	0	0	0	0.01	0.02	0.02	0.13	0.31	0.41
99	0	0	0	0	0	0	0	0	0	0	0	0	0.01	0.02	0.03	0	0	0
100	0	0	0	0	0	0	0	0	0	0	0	0	0.06	0.15	0.22	0	0	0
107	0	0	0	0	0	0	0	0	0	0	0	0	0.01	0.04	0.06	0	0	0
108	0	0	0	0.01	0.02	0.02	0	0	0	0	0	0	0	0	0	0	0	0
111	0	0	0	0.03	0.07	0.11	0	0	0	0	0	0	0	0	0	0	0	0
114	0	0	0	0	0	0	0	0	0	0.02	0.05	0.07	0	0	0	0	0	0

Table 5-1 showing 18 hazard scenarios for 6 magnitudes of rock and debris slide for 1yr, 3yr and 5yr return period in different mapping units

low i.e. 0.004 (Fig 5-9) because of the smaller area as compared to the mapping unit which result low hazard. The hazard for debris slide magnitude II is having landslides in 9 different locations of the road study area as shown in (Table 5-1), where 66th unit is showing the highest probability of 0.32 in 5yr return period and lowest probability obtained in 108th unit as 0.02 in 5yr return period (Fig 5-11). The hazard probability in 108th unit for 3yr and 5yr was found to be same 0.2 (Table 5-1), which is because of the same spatial probability which equalize different temporal probability. The variation of hazard particularly in these landslides is because of the spatial probability which differ in these units. Among these units 20th unit is having high hazard in 1yr, 3yr and 5yr scenario due to high spatial probability (Table 5-1). As shown in (Table 5-1) the hazard for debris slide magnitude III is obtained in 2 units i.e. in 66 and 84. The hazard for this category of landslide in these units is highly different from each other. The 66th unit is having high hazard of 0.77 in 5yr return period while the hazard probability in 84th unit is 0.06 in 5yr return period. High hazard in 66th unit for this category of landslide is because of high spatial probability i.e. 0.78 (Fig 5-9) and high temporal probability i.e. 0.98 (Fig 5-11), which is quite less in 84th unit of the study area. Both of these locations have bigger magnitudes of landslides but show different hazard values which show the uncertainty with occurrence of landslides.

Rock slide magnitude I in this study has been observed in 5 units of the study area (Table 5-1). The highest hazard value was observed in 114th unit i.e.0.07 and the lowest value was observed in 84th unit i.e. 0.004 (Table 5-1). Unit number 65 and 72 has high frequency of occurrence (Fig 5-12) but show less hazard due to smaller area of the landslide as compared to the mapping unit which it belongs, resulting low spatial probability (Fig 5-10). Low spatial probability in 84th unit also decrease the hazard value which have the same frequency of occurrence during 15 years as compared with 16th and 114th unit of the study area. The hazard scenario in rock slide magnitude II is totally different from other category of landslides in this study. As discussed above in the (Section 5.3) this scenario have landslides in 41 mapping units and only 9 units have no landslides. The highest hazard for this category of landslides is found in the 13th unit i.e.0.58 in 5yr return period which has high temporal probability of 0.87 (Fig 5-12) and high spatial probability of 0.79 (Fig 5-10). Lowest hazard value is shown by many units which show a frequency of 1 in 15 years due the variation in spatial probability changes the value for hazard. The hazard value for rock slide magnitude III has landslides on 8 locations of the study area (Table 5-1). Rock slide magnitude III show an equal distribution of hazard probabilities in all landslide containing mapping units except the 92, 93 and 96. Among these units 92 and 93 have same frequency of occurrence for landslides while landslides in 96th unit have occurred once in 15 years (Fig 5-8). The variation in hazard of both the units i.e.92 and 93 is because of the area of the landslides which changes the value for spatial probability (Fig 5-10). The highest hazard was found in 55th unit of the study area i.e. 0.69 in 5yr return period and lowest was found in 96th of 0.14 in 5yr return period.

By analysis of various hazard scenarios it was found that the hazard value for landslides in this research is highly dependent value obtained from the area of the landslides w.r.t. area of corresponding mapping unit i.e. spatial probability.

5.5. Vulnerability Analysis

The fundamental definition of physical vulnerability is the estimation of damage of an element at risk due to a hazardous phenomenon. In this study a quantitative vulnerability assessment was done for various vehicles using the traffic information and road damage by using historical landslides data as discussed in (Section 4.2.5). The vulnerability for various elements i.e. different vehicles and road was estimated on the basis of hazard scenarios obtained in the (Section 5.4).

5.5.1. Vehicle Density

For calculation of vulnerability for vehicles, initially vehicle density was calculated on different landslide containing road sections. Vehicle density for different types of vehicles was estimated on the basis of road length of those units which have landslides, average speed of different type of vehicles and average daily traffic (ADT). ADT was calculated from daily traffic data as shown in (Table 4-3), where it was observed that the daily movement of two wheelers are maximum as compared with the four wheelers and big vehicles. The movement of big vehicles was only done for public transportation and supply of food materials for day to day life, which was quite less (i.e. 25.7 per day) due to the low

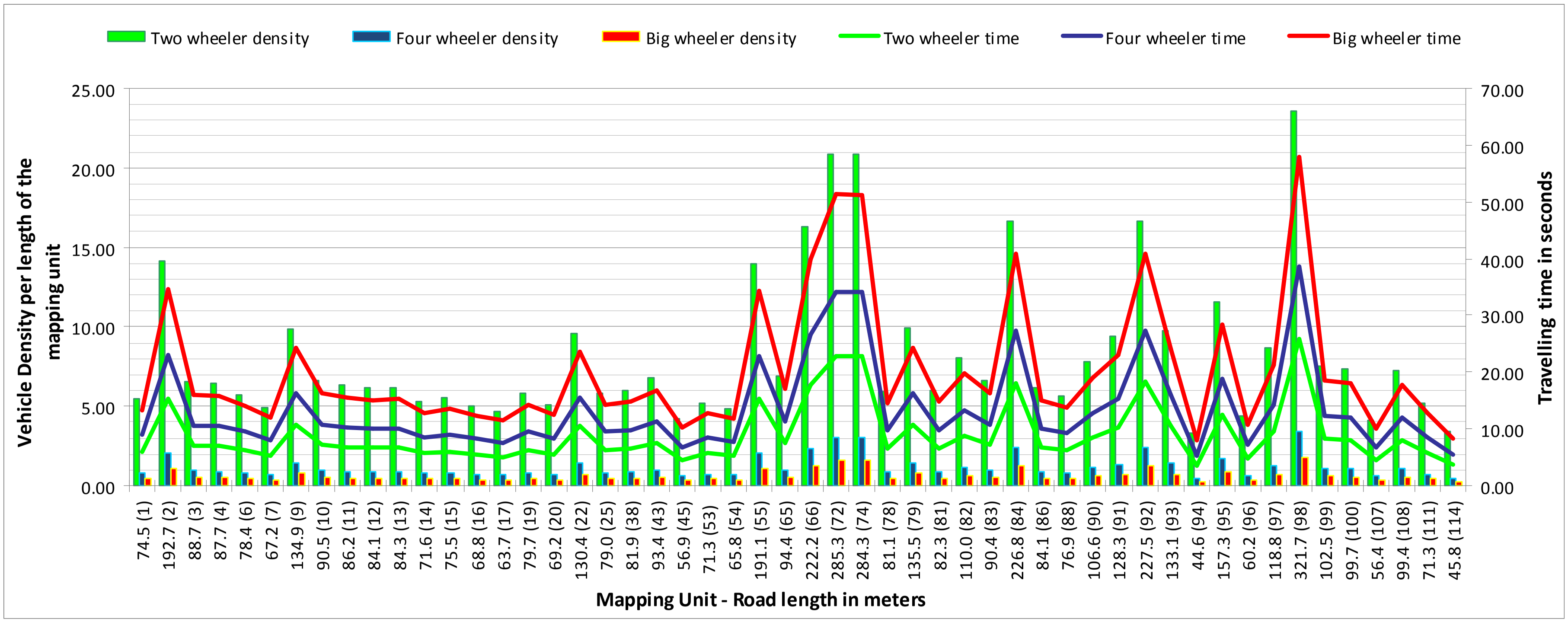

Figure 5-13 showing the vehicle density and travelling time for different types of vehicles

population density in the study area. The movement of two wheelers is maximum (i.e. 1319.4 per day) as it is the most convenient and economic for movement of population staying in the area. The high density of two wheelers is also due to the neighbourhood visitors who pay maximum visit to this place for its scenic beauty and picnic locations and prefer to be in two wheelers. The density of four wheelers is moderate (i.e. 97.8 per day) as it is used only for the private and tourist transport which came from long distance. From detailed field survey it was observed that the average speed of two wheeler, four wheeler and big vehicles are 45 km/hr, 30km/hr and 20km/hr respectively. The speed of two wheelers is maximum because of the size and easy handling capacity. The road corridor is narrow and the big vehicles are always loaded and occupy more space on road so to avoid accident on road they runs with minimum speed.

The vehicle density for various vehicles is given in (Fig 5-13). The travel time for small vehicles to the individual road section is minimum as compared to the four wheelers and big vehicles in each road section, which is because of the average speed of the two wheelers is more than the speed four wheelers and big vehicles. The highest length of the road was found to be in on 98th unit of the study area i.e. 321.7 meters, while the lowest road length was found in 114th unit i.e. 45.8 meters. The highest vehicle density was also found in the 98th unit i.e.23.6 for two wheelers, 3.43 for four wheelers and 1.83 for big vehicles per length of mapping unit. The highest vehicle density was because of the maximum length of the road section. The lowest vehicle density was found to be in 114th unit i.e. 3.36 for two wheelers, 0.46 for four wheelers and 0.23 for big vehicles, which is because of the small road length in this unit. The vehicle density in some road sections was found below one. These decimal values is considered as no vehicle in the road section, but actually the road unit length is small and average speed is enough to cross the unit quickly so that not a single vehicle will present at particular time. It was also observed that the longer the road length, higher is the travel time and higher is the vehicle density in every road section of the study area. In whole it was observed that the vehicle density for two wheelers is maximum while the vehicle density for big vehicles for is minimum, which is due to high ADT of two wheelers as compared to the big vehicles on the road sections of the study area.

5.5.2. Vehicle Vulnerability

Vulnerability of vehicles is highly dependent on the magnitude and proximity to the landslides. From various literature reviews it was analysed that the vulnerability of vehicles due to landslides are very much difficult to estimate due to dynamism of the vehicles in different time. A quantitative estimation of vulnerability in this study was attempted referring various literatures, which was done on the basis of absence and presence of particular landslide type on the different road section as discussed in (Section 4.2.5.1) with the vehicle density of different types of vehicles on different road sections.

	Debris Slide I	Debris Slide II	Debris Slide III	Rock Slide I	Rock Slide II	Rock Slide III
Two Wheeler	0.01	0.02	0.02	0.02	0.06	0.07
Four Wheeler	0.22	0.27	0.29	0.22	0.26	0.28
Big Vehicles	0.19	0.25	0.30	0.24	0.31	0.38

Table 5-2 showing the coefficients obtained from non-linear regression of landslide with ADT of different vehicle type

The result obtained from the non-linear regression as discussed in (Section 4.2.5.1) was shown in the (Table 5-2). The values obtained for various categories of landslide follows an increasing trend with increase in magnitude of different type of landslide.

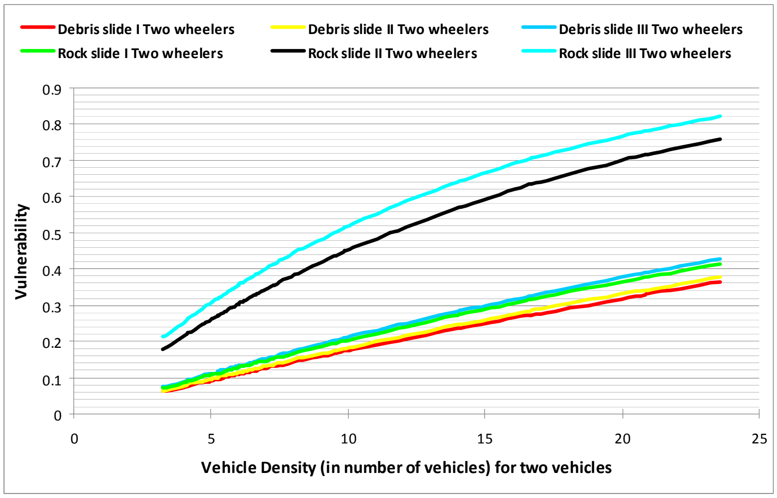

Figure 5-14 showing the vehicle vulnerability curve of two wheelers for all type of landslide

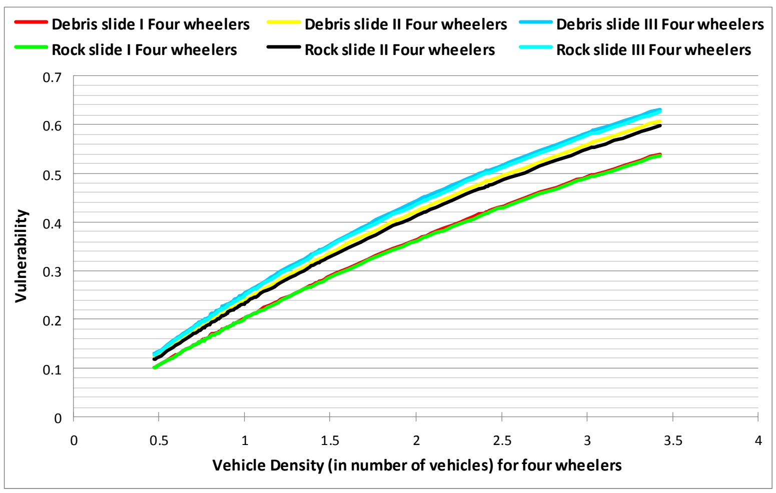

Figure 5-15 showing the vehicle vulnerability curve of four wheelers for all types of landslides

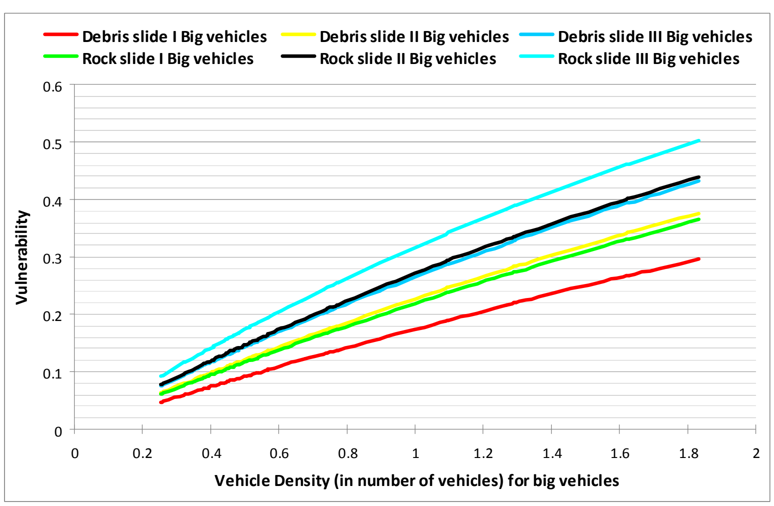

Figure 5-16 showing the vehicle vulnerability curve of big vehicles for all types of landslides

The vulnerability value of two wheelers due to all the landslides was given in (Fig 5-15). The result shows a higher value for the all magnitudes of rock slides while lower value for all magnitudes of debris slides. The maximum value for vulnerability of two wheeler due to rock slide magnitude I is 0.41 (Fig 5-15) which is almost equal to the highest vulnerability value of debris slide magnitude III for two wheelers. This reveals that the damage potential for rock slide magnitude I is almost same as damage potential of debris slide magnitude III. Logically, if we compare the vulnerability of a two wheeler due to a magnitude I (0 - 1000m^3) of debris slide and same magnitude of rock slide, the damaging potential of a rock slide will be higher due to its bigger material size and momentum due to the material size as compared to the material size of debris slide, also it is possible that, if a magnitude I of rock slide hits a two wheeler then the vulnerability should be 1. But in this study the vulnerability values for rock slide magnitude III (> 10,000 m^3) was not showing 1(Fig 5-15), which may be due to the limitation of the model to reach the expected accuracy. The highest vulnerability value for two wheeler due to rock slide magnitude III was found to be 0.82 (Fig 5-15), because of the high density of rock slide in the study area.

The vulnerability values for four wheelers are shown in (Fig 5-16). Comparing the results for four wheelers due to rock slide magnitude I, II, III and debris slide magnitude I, II, III in (Fig 5-16) it was observed that the vulnerability values has very less change for both the scenarios. The highest value obtained for four wheelers due to rock slide magnitude III is 0.63 and value obtained for debris slide magnitude III is 0.62 which is almost same while the highest value for rock slide magnitude I and debris slide magnitude I is 0.54 and 0.53 respectively. The small change in vulnerability between these two magnitude type landslides is because of the change in vehicle density.

The results of vulnerability for big vehicles shows an appreciable difference in rock slide magnitude I, II, III and debris slide magnitude I, II, III (Fig 5-17). It was observed that the vulnerability curve for rocks slide magnitude II and debris slide magnitude III are almost same, which results in the same damaging potential capacity of these types of landslides. The same was also observed for rock slide magnitude I and debris slide magnitude II. Highest vulnerability of big vehicles for rock slide magnitude II is 0.53 and the lowest value is 0.09, while the highest vulnerability value of big vehicles for debris slide magnitude II is 0.37 and lowest value is 0.07(Fig 5-17). This low value of debris slide magnitude II is because of the low density of landslides as compared to the rock slide magnitude II (Fig 5-9). Decrease in vulnerability value of big vehicles was also observed for debris slide magnitude III as compared to rock slide magnitude III (Fig 5-17). As a whole it was observed that the vulnerability of different magnitude of rock slide is high for any different vehicles than different magnitudes debris slide, which is because of bigger material size and high damaging capacity of rock slide. This gives the high vulnerability of two wheelers due to rock slides than compared to the four wheelers and big vehicles rather than all magnitudes of debris slides.

5.5.3. Road Vulnerability

Vulnerability of the road is associated with the magnitude of landslide which is responsible for the damage of the road or in simple terms what is the damage to road by particular type of landslide?. In this study a direct vulnerability of road was estimated on the basis of length of the road damaged, slide materials on the road, cost of removing debris from the road and cost of making a new road as discussed in the (Section 4.2.5.2). For this a details of cost for making a new road, its repairing cost, excavation of slide materials was estimated during field survey.

Cost Details	INR	US $
Cost of New Road Per Km	7000000	175000
Cost of New Road Per M	7000	175
Repairing Cost of Road Per Km	700000	17500
Repairing Cost of Road Per M	700	17.5

Table 5-3 showing the cost details of making a new road and repairing cost

Basically the cost of road includes road cutting and surfacing. It was very much difficult to obtain the details of every cost for cutting and surfacing due to shortage of time. So, cost of making a new road per km was directly obtained from BRO i.e.70 lakhs, as shown in (Table 5-3). Repairing cost was also obtained from BRO which is only 10% of the construction cost of the new road i.e. 7 lakhs as shown in (Table 5-3). All these amount are then converted to US $.

Details	Cost
Cost of PC-200 excavator for 1-hour	1100 INR
Bucket capacity of PC-200	1.8 m^3
Actual Bucket of PC-200 during work	1.5 m^3 x 2 bucket per min
Time taken for evacuation of 3000 m^3 in min	1000 min
Time taken for evacuation of 3000 m^3 in hours	16.66 hours
Cost for 16.66 hours for PC-200 in INR	18333.33 (INR)
Cost of 2 labours for 16.66 hours in INR	173.70 (INR)
Cost of 1 supervisors for 16.66 hours in INR	208.33 (INR)
Total cost for removing 3000 m^3 in INR	191415.33 (INR)
Total cost for removing 3000 m^3 INR	467.88 ($)
Cost of removing for 1m^3 in US $	0.16 ($)
Removal time for 1m^3 in min	0.33 min

Table 5-4 showing the excavation cost time for removing 1m^3 of slide materials using PC-200 excavator

I found it very difficult to estimate the cost of removing 1m^3 of slide material. So, for estimating the excavation cost of 1m^3 of slide materials, evacuation cost of 3000 m^3 of slide materials calculated as data collected from BRO. Initially a total cost of single PC-200 excavator i.e. 1100 INR per 1 hour including the operator, fuel and hydraulics was obtained. The use of a PC-200 is highly suitable in these roads because the road width is very narrow and highly unstable, big machines like PC-500 and PC-700 occupy more space and cannot work with full flow. The bucket capacity of the PC-200 machine was observed to be 1.8 m^3. But the actual bucket load during operation of the machine is 1.5 m^3. The bucket doesn't get full capacity because of size of the material is not flexible to occupy the space inside the bucket leaving an empty space. It was observed that in 1 minute PC-200 can make two runs i.e. loading and unloading. So, for evacuation of 3000m^3 of slide materials it will take1000 minutes. 1000 minutes is also equivalent to 16.66 hrs. So, the cost of running a PC-200 excavator is about 18333.33 INR. Apart from that, minimum of two labours is appointed on the spot for some manual operation which is 125 INR each in one day, so for 16.66 hours the cost of 2 labours is be 173.70 INR. To organise the work in full flow 1 supervisor is also appointed, which cost 300 INR per day. So, for 16.66 hours the supervisor cost around 208.33 INR. The total cost for this work force including a single PC-200 excavator for excavating 3000m^3 of material was around 18356.25 INR or 458.91 $ where, 1$ = 40 INR, and finally the cost of evacuating 1m^3 of material is 0.15 $ as shown in the (Table 5-4).

The vulnerability in this study needs a record of accumulated material on the road due to landslides. Observing the record of landslides from BRO it was found that, on every occurrence of landslide, there is a record of slide materials. These are the slide material released form individual slide which accumulated on a portion of road. Majority of the material falls into the high flowing Bhagirathi River. The accumulation of the material on the road is highly depending on the speed with which a landslide triggers, width of the road to hold the material and the magnitude of the slide which momentum accelerates the material to fall downward due to high slope. Some time higher magnitude slide accumulates larger amount of material which stops the communication link for couple of days. Material which falls on the road due to particular slide or evacuated was recorded by BRO officials. BRO officials also record the length of the road which was damaged by a particular slide. So, with the help of these records we found out the cost of removal of different accumulated slide materials on the road for different landslide types with the help of our prepared data (Table 5-4). It was observed that almost every slide accumulates slide material on the road. So, naturally the estimation of vulnerability will be for different road sections, but logically vulnerability of road due to a particular landslide is a single value (i.e. from 0 to 1), for example the vulnerability (damage) of road due to rock slide magnitude III (> 10,000m^3) is 9 (i.e. 90% damage). So, we take the average value of all the deposited slide material and all the road length for particular magnitude type landslide. This average value gives overall idea of deposited slide material and road length affected by a particular magnitude type landslide. From these collected and processed data about the cost of road, removal cost of slide materials (m^3), length of road damage and repairing cost we estimate the vulnerability of different slides using (Eq.4-6) as discussed in (Section 4.2.5.2).

Landslide Types	Vulnerability	Road length (km)	Material (m^3)
Debris slide magnitude I	0.07	0.02	250
Debris slide magnitude II	0.6	0.04	927
Debris slide magnitude III	0.9	0.11	600
Rock slide magnitude I	0.3	0.03	567
Rock slide magnitude II	0.7	0.06	837
Rock slide magnitude III	0.9	0.07	1007

Table 5-5 showing the vulnerability of road for different magnitude type landslides

The vulnerability estimated for different slides types with the average road length and average material accumulated was shown in (Table 5-5). It was observed that the vulnerability of road for debris slide magnitude I is lowest i.e. 0.07 (Table 5-5) as compared to the other type of landslides. The low damaging capacity of this particular type of landslide was due to the low magnitude which can only covers the road with the slide materials of 250 m^3 (Table 5-5). The low damage potential to this particular slide also surveyed from BRO office. The highest vulnerability value was obtained for debris slide magnitude III i.e. 0.9 (Table 5-5). This reflects that this particular slide can damage the road upto 90% , which is due to the speed of the bigger magnitude landslide and huge material. The vulnerability of rock slide is highly different from debris slides due to the difference in size of the material. The result of the vulnerability road due to rock slides was shown in (Table 5-5). Rock slide magnitude I shows a vulnerability of 0.3 for the road, which shows the damage to the upper portion of the road only, while rock slide magnitude II shows a vulnerability of 0.7 for the road and the highest for this category was observed for rock slide magnitude III i.e.0.9, which is because of the bigger size than other slides.

5.6. Direct Risk to Vehicles

Risk to any element is directly related to the spatio-temporal component of a damaging phenomenon and the effect of the natural phenomenon on that particular element at risk. Landslide risk assessment for individual element in this study is done by multiplying individual scenarios of landslide hazard for different landslide type, vulnerability of the elements at risk and amount of those elements at risk i.e. different vehicles and road. Direct risk for different vehicles and road is estimated on the basis of (Eq.4-6) as discussed in (Section 4.2.6). Initially it was considered that all the vehicles passing on the road are manufactured by India. The cost of various vehicles was estimated for different vehicles passing on the road as shown in (Table 5-6).

Type	INR	US ($)
Two Wheeler	45000	1125
Four Wheeler	650000	16250
Big Vehicles	1,500,000	37500

Table 5-6 showing the cost of different vehicles passing on the road corridor

Type	Debris Slide I			Debris Slide II			Debris Slide III			Total
	1 yr	3 yr	5 yr	1 yr	3 yr	5 yr	1 yr	3 yr	5 yr	
Two wheeler	0.6	1.3	2	71	169	231	161	272	300	1209
Four wheeler	13	28	35	1812	4309	5908	3628	6114	6747	28596
Big vehicles	17	35	43	2374	5626	7693	5426	9147	10094	40456
Total	31	65	80	4258	10105	13833	9215	15533	17141	70260

Table 5-7 showing specific risk ($) of two wheelers, four wheelers and big vehicles due to Debris slide I, II and III in 1yr, 3yr and 5yr return periods for the road stretch

Observing the columns in (Table 5-7) we can analyse that the specific risk for two wheelers due to debris slide magnitude I in 1yr, 3yr and 5yr return period was very low as compared to four wheeler and big vehicles for the whole road stretch. The highest value of specific risk was observed for big vehicles in 5yr return period i.e.43 $, for four wheelers 35$ and for two wheelers 2 $ as shown in (Table 5-7). The occurrence of debris slide I is small in size and has occurred in only one location i.e. 72nd unit as discussed earlier in (Fig 5-9). The low value of risk is because of the low hazard (Table 5-1). The risk for two wheelers is very less as compared with the four wheelers and big vehicles, which is because of the low cost of two wheelers as compared with the four wheeler and big vehicles (Table 5-7). The risk for all the vehicles due to debris slide magnitude I was found to be 31 $ in 1yr, 65$ in 3yr and 80$ in 5yr return period (Table 5-7). The risk estimated for two wheelers, four wheelers and big vehicles due to debris slide magnitude II was high for the whole road stretch as compared to the debris slide magnitude I as shown in the (Table 5-7). The highest value obtained for two wheelers due to debris slide II is 169 $, for four wheelers 5908 $, and for big vehicles 7693 $ (Table 5-7) in 5yr return period. It was observed that the debris slide magnitude II possesses higher risk than the debris slide magnitude I which is because of two reasons; (i) high vulnerability of two wheelers, four wheelers and big vehicles due to debris slide magnitude II (Fig 5-14; Fig 5-15; Fig 5-16) as vulnerability increases with increase in magnitude of landslide, (ii) higher hazard for debris slide magnitude II in 1yr, 3yr and 5yr return period as compared with the debris slide magnitude I (Table 5-1). Total risk due to debris slide magnitude II for all the vehicles in the road stretch was observed 4258 $ in 1yr, 10105 $ in 3yr and 13833 $ in 5yr return period, which was more than 100 times higher than debris slide magnitude I. The specific risk of two wheelers, four wheelers and big vehicles due to debris slide magnitude III is highest among the debris slides in this study (Table 5-7). The highest value of risk for two wheelers is 300 $, for four wheelers 6747 $ and for big vehicles 10094 $ (Table 5-7) in 5yr return period. The increase in value of risk for debris slide magnitude III is because of the size of landslide which increases the spatial probability (Fig 5-9), with increase in hazard value. Apart from hazard values, the increase in risk values is also due to increase in vehicle density for different vehicles in the road sections which has increase the vulnerability values (Fig 5-14; Fig 5-15; Fig 5-16). The increase in vehicle density is because of the increase in length of the road (Fig 5-13) which is quite higher for debris slide magnitude III with comparison of other debris slides. The risk value for different vehicles in other return periods i.e. 1yr and 3yr has also increased upto greater extent which is also due to the above reason. The low risk value of two wheelers was due to low cost of two wheelers as compared to the four wheelers and big vehicles (Table 5-9). Total risk for all the vehicles in the road stretch was observed 9215 $ in 1yr, 15533 $ in 3yr and 17141 $ in 5yr return period, which was more than 200 times higher than debris slide magnitude I in all return periods and double of debris slide magnitude II. The total risk for two wheelers, four wheelers and big vehicles was found to be 1209 $, 28596 $ and 40456 $ respectively for all magnitudes of debris slides in all return periods. Combining all the values we found that overall risk due to all magnitudes of debris slide for all the vehicles was 70260 $ (Table 5-7). The details of all individual risk values are shown in the Appendix 2-A, 2-B, 2-C.

Type	Rock Slide I			Rock Slide II			Rock Slide III			Total
	1 yr	3 yr	5 yr	1 yr	3 yr	5 yr	1 yr	3 yr	5 yr	
Two wheeler	6.5	16	24	760	1835	2538	557	1263	1659	8658
Four wheeler	135	342	493	7863	18976	26224	5623	12757	16769	89183
Big vehicles	186	469	673	12316	29704	41033	10028	22762	29928	147101
Total	328	827	1191	20939	50514	69795	16208	36783	48357	244942

Table 5-8 showing specific risk ($) of two wheelers, four wheelers and big vehicles due to Rock slide I, II and III in 1yr, 3yr and 5yr return periods for the road stretch

Specific risk for different vehicles due to rock slide I, II and III in different return periods for the whole road stretch was shown in (Table 5-8). The value of risk was found to be low for this category of landslide due to low density of rock slide magnitude I occurring only in 5 locations of the study area (Fig 5-10). The highest value for two wheelers was 24 $ in 5yr return period (Table 5-8). Risk values in this category of slide increases for four wheelers and big vehicles i.e. 493 $ and 673 $ respectively. The higher risk value for four wheelers and big vehicles was because of the higher cost (Table 5-6). Total values of risk for all the vehicles was found to be 328 $ in 1yr, 827 in 3yr and 20939 in 5yr return period (Table 5-8). The specific risk of two wheelers, four wheelers and big vehicles due to rock slide magnitude II was found to be high (Table 5-8) the whole road stretch of the study area, because of the higher density of rock slide magnitude in this study (Fig 5-10). The risk values for different vehicles in this category of landslides are higher as compared with rock slide magnitude I. The highest risk value for two wheelers, four wheelers and big vehicles was found to be 2538 $, 26224 $

and 41033 $ (Table 5-8) respectively in 5yr return period for the whole road stretch. The higher risk value was because of increase in vulnerability which was due to the higher vehicle density as shown in (Fig 5-13). The lowest value for two wheelers, four wheelers and big vehicles was found to be 760 $, 7863 $ and 12316 $ respectively for the whole road stretch (Table 5-7), in 1yr return period, which is because of the low hazard as shown in (Table 5-1). Overall risk values of different vehicles for rock slide magnitude II was found high than other categories of landslides in this study, which is because of the high hazard and high vulnerability of higher magnitude type landslide. Total values of risk for all the vehicles due to rock slide magnitude II was found to be 20939 $ in 1yr, 50514 $ in 3yr and 69795 $ in 5yr return period (Table 5-8). The specific risk of two wheelers, four wheelers and big vehicles for rock slide magnitude III was shown in (Table 5-8). This category of landslide possesses highest risk to different vehicles than any other category of landslide individually in the study area. The occurrences of these landslides are very low (Fig 5-10) i.e. occurred in only 9 mapping units of the study area as compared to the rock slides magnitude II (Fig 5-10) which has occurred in 41 mapping units, but the area occupied by these landslides is quite high because of the higher magnitude as shown in (Fig 5-10). The highest value observed for two wheelers, four wheelers and big vehicles in 5yr return period was 1659$, 16769$, and 29928 $ respectively. The highest value for risk is obviously because of the higher magnitude, which results in higher hazard value (Table 5-1) and also due to higher vulnerability value which results from higher vehicle density (Fig 5-13) for this particular category of landslide. Total risk for all the vehicles in the road stretch was observed 16208 $ in 1yr, 36783 $ in 3yr and 48357 $ in 5yr return period, which was more than 40 times higher than debris slide magnitude I. It was also observed that the combine risk of rock slide magnitude II is 1.5 times higher than rock slide magnitude III in all return periods. The total risk for two wheelers, four wheelers and big vehicles was found to be 8658 $, 89183 $ and 147101 $ respectively for all magnitudes of rock slides in all return periods. Combining all the values we found that overall risk due to all magnitudes of debris slide for all the vehicles was 244942 $ (Table 5-8). The details of all individual risk values are shown in the Appendix 2-D, 2-E, 2-F.

Comparing the combine risk values for whole Debris slide magnitude and Rock slide magnitudes it was observed that overall risk to different vehicles was quite high for rock slides than debris slides, which was mainly due to the high occurrence of rock slide in the terrain.

5.7. Direct Risk to Road

Direct risk for road was estimated on the basis of different hazard scenarios for individual landslide type for different return period, vulnerability of the road estimated for different landslide magnitudes and repairing cost of the road as discussed in (Section 4.2.6).

Type	Debris Slide I			Debris Slide II			Debris Slide III			Total
	1 yr	3 yr	5 yr	1 yr	3 yr	5 yr	1 yr	3 yr	5 yr	
Road	19	41	51	36767	91061	129239	62744	106139	117567	543628

Table 5-9 showing the Specific risk ($) of road due to Debris slide I, II and III in 1yr, 3yr and 5yr return period for the whole road stretch

The specific risk of road due to debris slide magnitude I, II and III was shown in (Table 5-9). The risk for road due to debris slide magnitude I increase with hazard for 1yr, 3yr and 5yr return period. The highest value of risk has been observed 51$ (Table 5-9) due to single occurrence of landslide for this type as mentioned earlier in (Fig 5-9). The overall risk value for this unit is low because of the low hazard (Table 5-1) and also due to low vulnerability (Table 5-3). The risk of road due to debris slide magnitude II was quite high (Table 5-9) which was almost 2000 times higher than debris slide magnitude I. The high value is because of the increase in number of occurrences of landslides which was found in 9 units of the study area (Fig 5-9). Risk values for this category were higher than the debris slide magnitude I, because of the higher magnitude which possesses higher hazard and higher vulnerability. The highest value of risk was found to be 129239 $ for the whole road stretch (Table 5-8) for 5yr return period for the whole road stretch. Debris slide magnitude III generates highest risk among all magnitudes of debris slide for the road as it has high hazard and high vulnerability. Debris slide magnitude III has occurred in only 2 units of the study area as shown in (Fig 5-9). The highest value of risk was found 117567 $ in 5yr return period for the whole road stretch which was due to high hazard (Table 5-1) i.e. 12 number of occurrences. The higher vulnerability is due to higher occupancy of road length (Fig 5-13) which is basically due to the bigger size of the slide. This category of slide possesses more than 2000 times risk as compared to debris slide magnitude I and a couple of times more than debris slide magnitude II. Overall risk was observed to be to be 543628 $ for all magnitudes of landslides and all return periods for the whole road stretch.

Types	Rock Slide I			Rock Slide II			Rock Slide III			Total
	1 yr	3 yr	5 yr	1 yr	3 yr	5 yr	1 yr	3 yr	5 yr	
Road	3012	7806	11495	205572	493944	681099	126413	288702	381911	2199955

Table 5-10 showing the Specific risk ($) of road due to Rock slide I, II and III in 1yr, 3yr and 5yr return period for the whole road stretch

The specific risk of road due to rock slide magnitude I, II and III for the whole road stretch in 1yr, 3yr and 5yr return period was shown in (Table 5-10). The rock slide magnitude I found in 5 units of the study area as shown in (Fig 5-10). The highest value of risk was found to be 11495 $ (Table 5-10) in 5yr return period for the whole road stretch, which is much higher than debris slide magnitude I. Specific risk of road for rock slide magnitude II shows the highest value of risk among all the landslides categories in this study (Table 5-10). The high risk value is due to the more occurrences i.e. 41 units of the study area (Fig 5-10). The highest risk value was obtained as 681099 $ for 5yr return period for the whole road stretch (Table 5-10). Risk possesses by this particular category of landslide is more than 60 times higher as compared to the rock slide magnitude I which is because of the higher occupancy of road due to high density of landslide. Rock slide magnitude II also possesses higher risk than rock slide magnitude III as shown in (Table 5-10). Specific risk of road for debris slide magnitude III was for the whole road stretch was shown in (Table 5-10). The risk value of road due to rock slide magnitude III has low value, than risk due to rock slide magnitude II due to less number of occurrences as compared to the rock slide magnitude II. The highest risk value for whole road stretch was found to be 381911 $ in 5yr return period. Overall risk for whole road for all magnitudes of landslides in all return period was estimated to be 2199955 $ (Table 5-10). As a whole it was observed that the risk for road was much higher due to rock slides in the area than debris slides. The total risk for all return periods with all magnitudes shows almost 4 times higher risk than debris slides in the study area. The detail of risk for road was provided in Appendix 3-A, 3-B, 3-C, 3-D, 3-E, and 3-F.

5.8. Indirect Risk Analysis

The risk generated due to the indirect impact of landslide which affects the normal life of the neighbouring society in terms of money and time is termed as "Indirect risk". In this study indirect risk was calculated for loss of profit for different business in Gangnani, Harsil and Sukhi top, which are the end stations after the study area in National Highway 108 as discussed in (Section 4.2.7). For estimation of indirect risk initially, field survey was done on different business type in Gangnani, Harsil and Sukhi top. Due to time constraint in this study only those business type are considered which affects the daily life of small population staying in the area i.e. different shops, restaurant, religious vendors, liquor shop, medicine store and variety store. Details analysis of loss to profit was estimated for various business types due to blockage of road which was due to removal of accumulated slide material for individual magnitude type landslide in peak season (Table 5-11 and Table 5-12).

Type	Number of shops	Daily Profit Per Shop Peak Season (INR)-(DPPSPS)	Daily Profit Per Shop Peak Season ($)-(DPPSPS)	Daily Profit all Shops Peak Season (INR)-(DPASPS)	Daily Profit all Shops Peak Season ($)-(DPASPS)	Profit loss for 1 hour ($)-(PFH)
Sweets Shop (SS)	3	200	5	600	15	1.25
Normal Restaurant (NR)	10	500	12.5	5000	125	10.41
Fruit Shop (FS)	4	250	6.25	1000	25	2.08
Religious Vendors	8	900	22.5	7200	180	15
Grocery Shop (GS)	2	400	10	800	20	1.66
Vegetable Shop (VegS)	5	200	5	1000	25	2.08
Variety Store (VS)	4	400	10	1600	40	3.33
Total	36	2850	71.25	17200	430	35.81

Table 5-11 showing the profit details for various shops in Gangnani

Types	Number of shops	Daily Profit Per Shop Peak Season (INR)-(DPPSPS)	Daily Profit Per Shop Peak Season ($)-(DPPSPS)	Daily Profit all Shops Peak Season (INR)-(DPASPS)	Daily Profit all Shops Peak Season ($)-(DPASPS)	Profit loss for 1 hour ($)-(PFH)
Sweets Shop (SS)	33	900	22.5	29700	742.5	61.87
Normal Restaurant (NR)	45	1200	30	54000	1350	112.5
Fruit Shop (FS)	39	700	17.5	27300	682.5	56.87
Religious Vendors (RV)	96	1100	27.5	105600	2640	220
Grocery Shop (GS)	28	500	12.5	14000	350	29.16
Vegetable Shop (VegS)	27	1000	25	27000	675	56.25
Variety Store (VS)	48	300	7.5	14400	360	30
Medicine Store (MS)	8	500	12.5	4000	100	8.33
Liquor Shop (LS)	3	1300	32.5	3900	97.5	8.12
Total	327	7500	187.5	279900	6997.5	583.1

Table 5-12 showing the profit details of various business types in Harsil and Sukhi Top

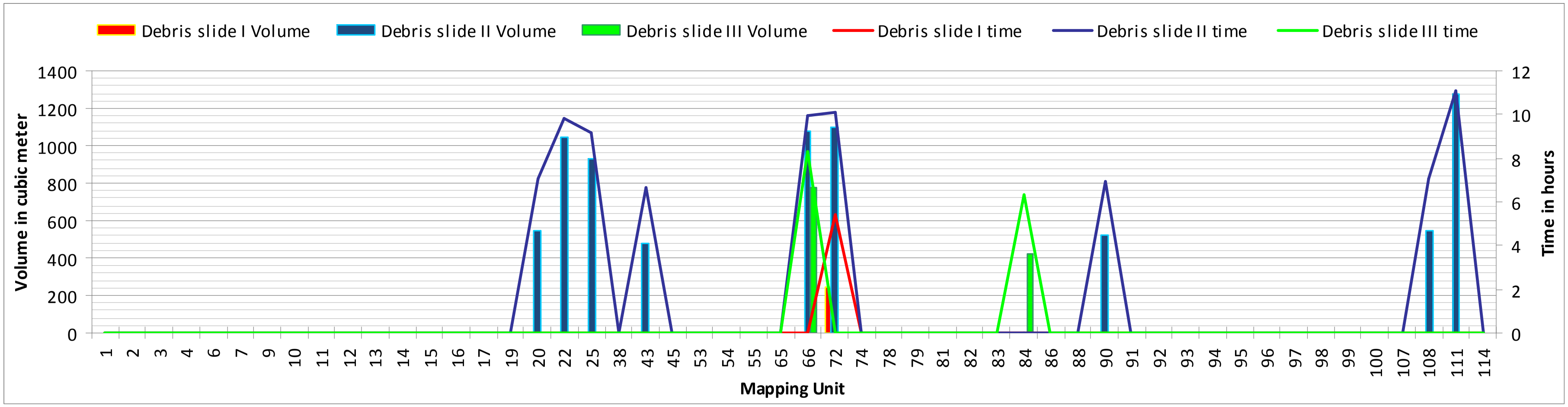

Figure 5-17 showing the volume of slide materials and evacuation time of slide materials for debris slides

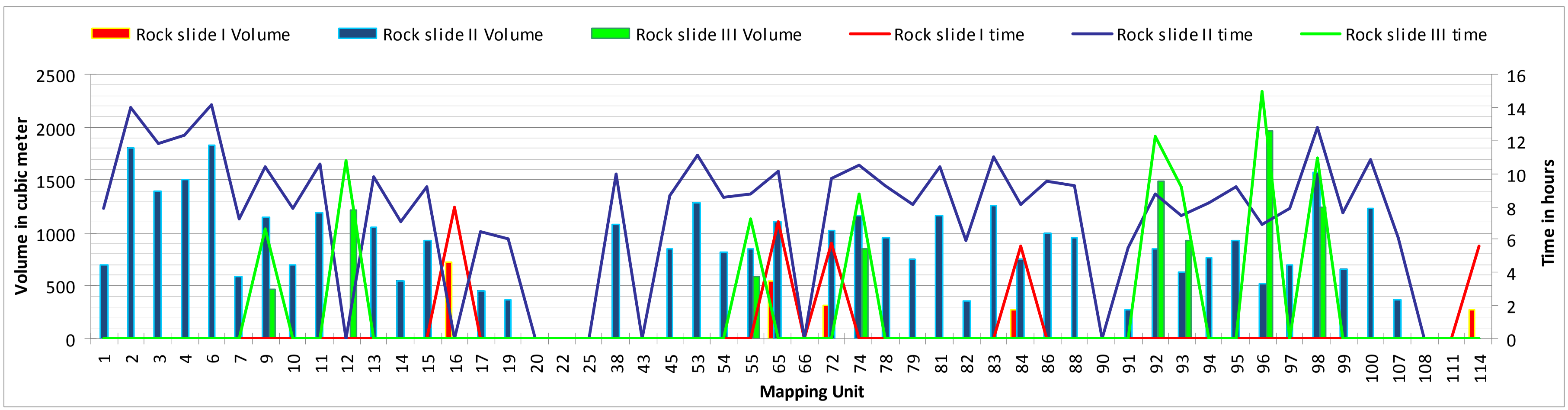

Figure 5-18 showing the volume of slide materials and evacuation time of slide materials for rock slides

As shown in (Table 5-11 and Table 5-12), it was found that various business in Gangnani was quite less as compared to the Harsil and Sukhi top because Gangnani is a small station which have very less population and only meant for small break during journey to Gangotri, which is one of the holiest places and attract different visitors and tourist from India and various part of world. Harsil and Sukhi top are the main stations after Uttarkashi which provide food and materials for daily living of the population and tourists residing in Gangotri. The highest numbers of shops are normal restaurants in Gangnani i.e.10 (Table 5-11), while 96 religious vendors in Harsil and Sukhi top (Table 5-12). The high number of religious vendors in Harsil and Sukhi top is due to the visit of many tourists and pilgrims who pay visit to Gangotri for offerings, for which they require religious materials. Daily profit for different individual business type per shop was given as DPPSPS (INR) in (Table 5-11 and Table 5-12) which was obtained by a field survey of 7 days. For estimation of profit for all shops the numbers of shops are multiplied with there corresponding DPPSPS (INR) to obtain DPASPS (INR) as shown in (Table 5-11 and Table 5-12). DPASPS (INR) is then converted to US $ i.e. DPASPS ($) as shown in (Table 5-11 and Table 5-12). During field survey it was found that the business was only done for 12 hours in a day i.e. 9.00 A.M to 9.00 P.M and rest of the time the shops are closed. So, profit done by different business types in 1 hour was given by PFH ($) for both the places (Table 5-11 and Table 5-12). Indirect risk for different magnitude of landslide type in this study is generated due to loss in profit of the local business. The loss in profit for local business was due to the accumulation of slide materials on the road corridor due to different landslide which blocks the communication link for this route. As this National Highway 108 is the only way for this route, visitors and tourist has to wait for hours for the removal of slide materials from the road which results in loss for local business. The time taken for removal of 1 m^3 of slide materials was 0.33 min as discussed in (Table 5-4). Total time taken for removal of various m^3 of slide materials for different landslides type was estimated and converted in hours as shown in (Fig 5-17 and Fig 5-18). Extra 4 hour was added for the time taken by an excavator and workers to reach the landslide spot as investigated during field survey. It was observed from the (Fig 5-17) that the accumulation of slide materials for debris slide I is the lowest i.e.250 m^3 in 72nd unit, which takes 5.3 hours to evacuate. The highest time taken for evacuation of debris slide material was observed for magnitude II of debris slide i.e.12.30 hours for evacuating 1275 m^3 materials in 111th unit (Fig 5-17). Debris slide magnitude III didn't have any high accumulation of slide materials because of the high magnitude the speed of releasing material is high which normally doesn't get accumulated in a road of small width, but leave some material on the road. The highest time taken for rock slide magnitude I is 8hours for 1200 m^3 of material in 12th unit as shown in (Fig 5-18). The highest time taken for rock slide magnitude II was observed in 6th unit i.e. 12 hours for 1800 m^3 of material. It was observed that rock slide magnitude III takes highest time for removal of slide materials among all categories of slides i.e.15 hours for 1950 m^3 slide materials as shown in the (Fig 5-18).

5.8.1. Indirect Risk for Gangnani

Gangnani is the northern end of the study area. Numbers of local business are very less because of less consumption of materials. Only normal restaurants are considered as main business type for the particular place, which also runs in less profit. This place is mainly used by the local people residing in the area for general activities. Indirect risk of various local businesses for different landslide type was estimated on the basis of number of particular shops and its profit loss due to road blockage in hours which was estimated in (Section 5.8).

Indirect risk for debris slide magnitude I for various shops in Gangnani was shown in (Table 5-13). The highest value of indirect risk for this particular landslide type was observed for RV i.e.81 $

(Table 5-13). It was observed that the number of RV was found to be 8 (Table 5-11), which was not the highest among shops but the profit done by this category of shop was quite higher than other shops which result in higher loss. RV is the shops which provides materials for religious offerings to god and is used by maximum people going to the area, increasing the sell with increase in profit. The lowest value of indirect risk for this category of landslide was found for SS (Table 5-13), due less consumption of sweet which results in less profit. Total indirect loss was observed to be 193 $ (Table 5-13).

Types	Debris Slide I	Debris Slide II	Debris Slide III	Rock Slide I	Rock Slide II	Rock Slide III	Total
Sweets Shop (SS)	7	97	18	40	469	101	732
Normal Restaurant (NR)	56	811	153	333	3909	840	6101
Fruit Shop (FS)	11	162	31	67	782	168	1220
Religious Vendors (RV)	81	1168	220	479	5628	1210	8786
Grocery Shop (GS)	9	130	24	53	625	134	976
Vegetable Shop (VegS)	11	162	31	67	782	168	1220
Variety Store (VS)	18	259	49	106	1251	269	1952
Total	193	2789	526	1145	13445	2890	20988

Table 5-13 showing the summarised Indirect loss ($) for various shops in Gangnani for all landslides types

The indirect risk generated due to debris magnitude II for various shops in Gangnani was shown in (Table 5-13). The highest value for indirect risk was obtained for RV i.e. 1168 $ because of the higher profit done by this particular shop as discussed above. It was observed that the loss in profit for NR (Table 5-13) due to debris slide magnitude II was also high i.e. 811 $ (Table 5-13). Loss for this slide is high due to the high number of these kind of shops and because of the high material accumulation in the road stretch (Fig 5-17), which block the road for maximum time resulting loss in profit. Other shops like SS don't make any big loss as profit done by these shops in normal situation is low (Table 5-13). Due to less dependency of low population on this particular station profit done by other shop like VegS, GS, and VS are very less resulting low indirect risk. Total indirect risk due to debris slide magnitude II was found to be 2789 $ which is 14 times higher than indirect risk generated by debris slide I.

Indirect loss due to debris slide magnitude III was not so high as compared to the debris slide magnitude II which is because of the low accumulation of the slide materials on the road (Fig 5-17), results in less time. Low accumulation of slide materials for this particular type of landslide was due to high magnitude of landslide as discussed in (Section 5.5.3). The vulnerability of debris slide magnitude III for the road was 0.9 (Table 5-3). So, if the road has vulnerability of 0.9 then the damage will be 90% which results in major destruction of road and will take around 4to5 days for repairing. But in context of indirect risk, only time for removing slide material was considered as there is no such record of full preparation of road. Overall it was found that the indirect risk due to debris slide magnitude II was the highest among debris slides for RV (Table 5-13). Other shops suffer less from road blockage due to less profit. Debris slide magnitude I have the lowest indirect risk because of less time for road blockage (Fig 5-17). The total indirect risk for this kind of landslide for all shops in Gangnani was estimated as 525 $.

Indirect risk due to rock slide magnitude I for all shops in this study was shown in (Table 5-13). It was observed that indirect risk for this particular category of landslide due to accumulation of slide materials in 114 and 84 for all the shops are same which is because of the same removal time (Fig 5-18) of slide material in these units. These values are also lowest value of indirect risk for this category of landslides in the study. Highest value of indirect risk was observed for RV (Table 5-13) i.e. 479 $ for all the rock slide magnitude I occurrences. This is due to the high accumulation of slide materials which take more time for removal of slide materials as shown in (Fig 5-18). Total indirect risk for rock slide magnitude I for all shops in Gangnani was estimated as 1145 $ (Table 5-13).

Rock slide magnitude II has high values of indirect risk for all kind of shops in this study as shown in (Table 5-13). The high values of indirect risk is due to numerous landslide occurrence rock slide magnitude II which results in high accumulation of slide materials on the road and takes longer time for removal (Fig 5-18) of slide materials. For this category of landslide the highest value of indirect risk was observed for RV i.e. 5628 $ (Table 5-13). The highest value was due to high loss in profit (Table 5-11) for RV which was due to more time for road blockage (Fig 5-18). The lowest value was found for SS i.e.6.42 $ (Table 5-13), which is due to lowest profit income by SS in the area. The loss of profit to the NR (Table 5-13) was also high for this category of landslide due to high profit (Table 5-11) by these shops which was comparatively higher than other shops in Gangnani. Total indirect risk was found to be 13445 $ for various shops in Gangnani due to rock slide magnitude II (Table 5-13).

The indirect risk for rock slide magnitude III has also high values as shown in (Table 5-13). Indirect risk was due to road blockage of 9 landslide occurrences which blocks the road corridor for hours (Fig 5-18). The highest value of indirect was found for RV i.e. 1210 $ for accumulation of slide materials in 96th unit of the study, because of high accumulation of slide materials which takes longer time for removing from the landslide site as shown in (Fig 5-18). The lowest value was observed for SS i.e. 101 $ (Table 5-13). The low value was because of the low profit done by the shop as shown in (Table 5-11).

Overall, value for indirect risk for rock slide was found to be highest among two types of landslide which is because of the higher density of rock slide as compared to debris slide in the study as discussed in the (Section 5.1). The indirect risk in Gangnani was observed mainly for RV (Table 5-13), as these shops makes maximum profit during the peak seasons and also necessary for the visitors who buy the require materials for offerings in Gangotri. Other shops only used by the local people in the study area which are very less. The highest total indirect risk for individual shops due to all landslides in the road stretch was found for RV i.e.8786 $ (Table 5-13), and total indirect risk for all the shops in Gangnani and for all the magnitude type landslides was estimated to be 20988 $ as shown in (Table 5-13). The details of indirect risk in Gangnani was provided in Appendix 4-A, 4-B, 4-C, 4-C, 4-D, 4-E, and 4-F.

5.8.2. Indirect Risk for Harsil and Sukhi Top

Harsil and Sukhi top are bigger stations than Gangnani for this route. The concentration of various business types was also high in these places as investigated from field survey. Tourist and visitors from various places takes rest during there long journey because this place is nearer to Gangotri. So, naturally during peak seasons this place is highly populated and the profit done by various business types was also high. As National Highway 108 is the only way to reach Harsil and Sukhi Top. The landslide occurrences in the road i.e. Bhatwari to Gangnani blocks the communication link creating high loss to the various business in Harsil and Sukhi Top. Indirect risk for various businesses in Harsil and Sukhi top was estimated on the basis of profit done by a particular kind of shop and profit loss due to road blockage in hours.

Types	Debris Slide I	Debris Slide II	Debris Slide III	Rock Slide I	Rock Slide II	Rock Slide III	Total
Sweets Shop (SS)	333	4817	908	1977	23217	4990	36240
Normal Restaurant (NR)	606	8758	1650	3594	42212	9072	65891
Fruit Shop (FS)	306	4427	834	1817	21340	4586	33312
Religious Vendors (RV)	1186	17126	3227	7028	82548	17741	128854
Grocery Shop (GS)	157	2270	428	932	10944	2352	17083
Vegetable Shop (VegS)	303	4379	825	1797	21106	4536	32946
Variety Store (VS)	162	2335	440	958	11257	2419	17571
Medicine Store (MS)	45	649	122	266	3127	672	4881
Liquor Shop (LS)	44	632	119	260	3049	655	4759
Total	3142	45393	8553	18628	218798	47023	341536

Table 5-14 showing the summarised Indirect loss ($) in profit for various shops in Harsil and Sukhi Top for all landslide types

Indirect risk for various business types in Harsil and Sukhi Top due to debris slide magnitude I was shown in (Table 5-14). Occurrence of landslide for this particular type was found only in 72nd unit of the study area (Fig 5-9). As the numbers of shops are more in this place, indirect risk for various business types was also high as compared to debris slide magnitude I in Gangnani (Table 5-13). The highest value of indirect risk was found for RV i.e. 1186 $ (Table 5-14), due higher number this kind of shops in Harsil and Sukhi Top (Table 5-12). The lowest value was found for LS i.e. 44 $ (Table 5-14). As this place is near to the Gangotri (i.e. holy place), consumption of alcohols are also less (Table 5-12). Total indirect risk estimated for various shops in Harsil and Sukhi Top due to debris slide magnitude I was 3142 $ (Table 5-14).

The indirect risk for various shops in Harsil and Sukhi Top was quite higher due to increase in accumulation of slide materials of the landslides. The indirect risk of SS was quite high (Table 5-14) due to higher number of shops in this place (Table 5-12). Consumption of medicine from MS (Table 5-36) was also observed in this place due to high concentration of people. The highest value of indirect risk was observed for RV i.e. 17126 $ (Table 5-14). High indirect loss was due to the more number of shops (Table 5-12) and higher profit done by this particular type. The lowest was observed for LS i.e. 632 $. The total indirect risk for all the business types was found to be 45393 $ for this category of landslides, the increase in value for this category of landslide was due to the increase in removal time of the accumulated material.

Debris slide magnitude III has lower value of indirect risk as compared to the debris slide magnitude II because of less accumulation of slide material as shown in (Fig 5-18). The highest value of indirect risk was found for RV i.e. 3227 $ (Table 5-14) and lowest value of indirect risk was found for LS, 119 $ (Table 5-14). The low value for this kind of shop was because of the low number and less profit (Table 5-12). Total indirect risk obtained for various shops due to this particular landslide was 8553 $ (Table 5-14).

Indirect risk for rock slide magnitude I was shown in (Table 5-14). The results shows that GS and VS has almost same indirect loss but have different number of shops in the area. The same value for these shops was due to the same profit loss per hour as shown in (Table 5-12) and also due to the same slide material accumulation resulting same removal time. The highest value of this category of landslide was found to be 18628 $ for RV (Table 5-14). This value of indirect risk for this kind of shop was quite high as compared with rock slide magnitude II in Gangnani (Table 5-13), which was due to high number of these kind of shops in Harsil and Sukhi Top (Table 5-12). The lowest value was observed for LS, which was due to less number of shops as discussed in (Section 5.8.1). Total indirect risk obtained for various shops due to this particular landslide was 18628 $ (Table 5-14).

Indirect risk of various shops in Harsil and Sukhi Top for rock slide magnitude II was found due to 41 locations in the study area because of higher density of landslide in this category. The summarised result reveals that this category of landslide also possesses high indirect risk to all the business types in the study area. The high value of indirect risk was found for RV, i.e. 82548 $ (Table 5-14), due to high accumulation of landslide materials in the road section which results in more removal time (Fig 5-18) and high loss in term of profit. The lowest value was observed for LS i.e.3049 $ (Table 5-14). It was observed that GS and FS have almost same value of loss to profit (Table 5-14), because of same profit done by both these shops for 1 hour (Table 5-12). The total indirect risk obtained for various business types was found to be 218798 $ (Table 5-14).

Indirect risk for different business types due to rock slide magnitude III was shown in (Table 5-14). It was observed that indirect risk to various business types for this particular category of landslide was lowest as compared to rock slide magnitude II, because of less accumulation of materials as compared to the rock slide magnitude II. The highest indirect risk was observed for RV i.e. 17741 $ (Table 5-14) due to high material accumulation, which has high removal time (Fig 5-18). The lowest indirect risk was observed for LS i.e. 655 $ (Table 5-14). The total indirect risk obtained for various business types was found to be 47023 $ (Table 5-14).

The indirect risk observed for Harsil and Sukhi Top due to slide material accumulation from various types of landslides was higher for RV as the number of this kind of shops are more and lowest was observed for LS which has less number of shops results in less consumption and less profit. Overall it was observed that the total landslide risk various shops in Harsil and Sukhi Top for all landslide type magnitudes was found to be 341536 $ as shown in (Table 5-14). Comparing the result of indirect risk it was observed that the indirect risk value for Gangnani was much low than indirect loss of Harsil and Sukhi Top which was mainly due to the higher number of shops in Harsil and Sukhi Top. But highest value of indirect risk was possessed by RV in both the areas because of the religiousness of the area.

5.9. Final Direct Risk

Final risk was estimated only for the direct impact of landslides on different vehicles and road as indirect loss was because of whole road. To obtain a final direct risk, all the specific risk of individual elements at risk (i.e. two wheelers, four wheelers, big vehicles and road) for all the magnitudes of debris and rock slides are individually added on the basis of 1yr, 3yr and 5yr return period as shown in (Fig 5-19). The final map was classified as Low (< 20000 $), Moderate (20000 - 40000 $), High (40000 - 60000 $) and Very High (> 60000 $) on the analysis done for combine risk as shown in (Fig 5-20). High risk for all the elements in 5yr return period was observed because of the high hazard probability as compared to 3yr and 1yr return period. The combine risk for all the elements

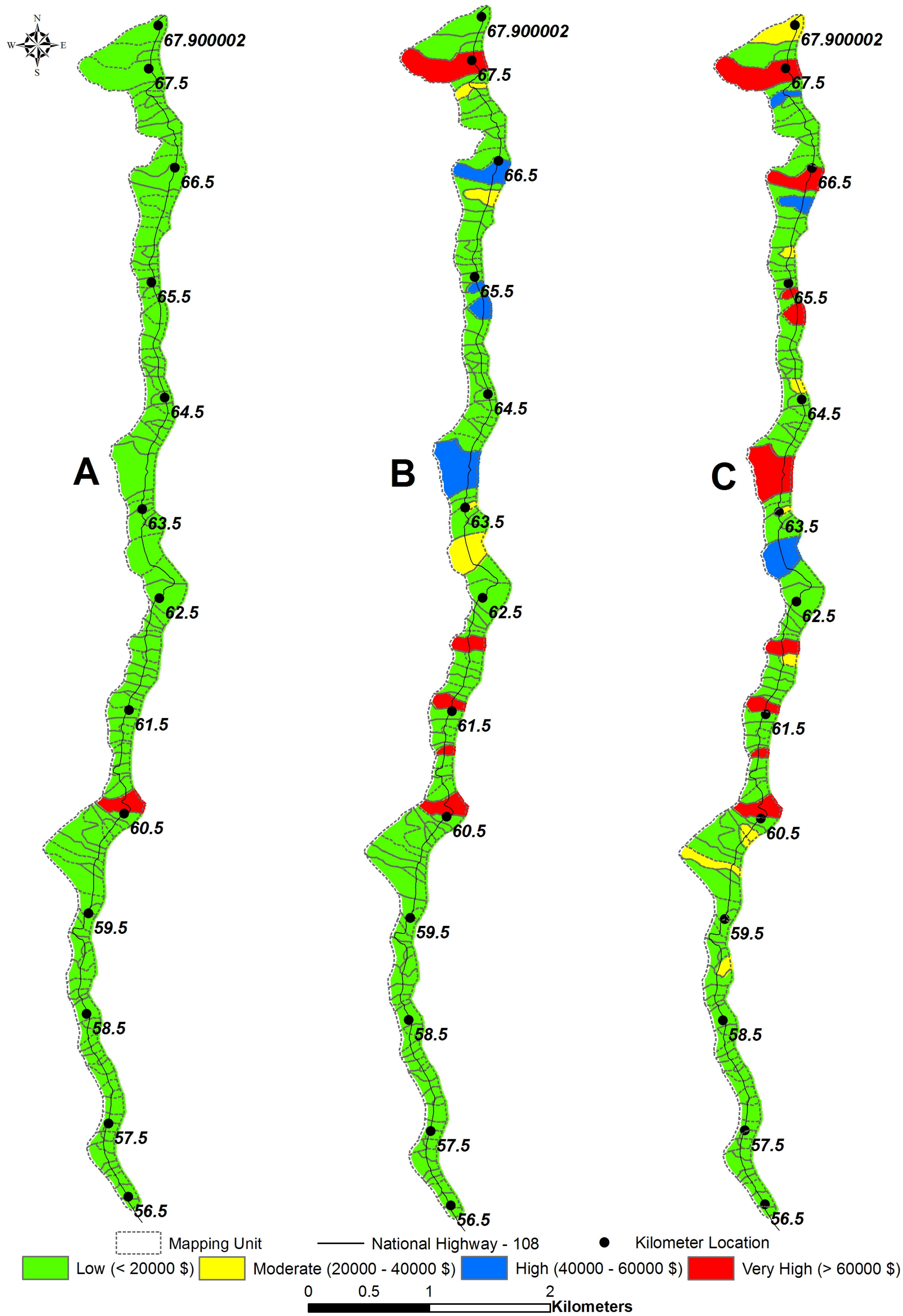

Figure 5-19 showing the final risk ($) of two wheeler, four wheeler, big vehicles and road for all magnitudes of debris and rock slide in 1yr (A), 3yr (B) and 5yr return period (C) in different mapping units

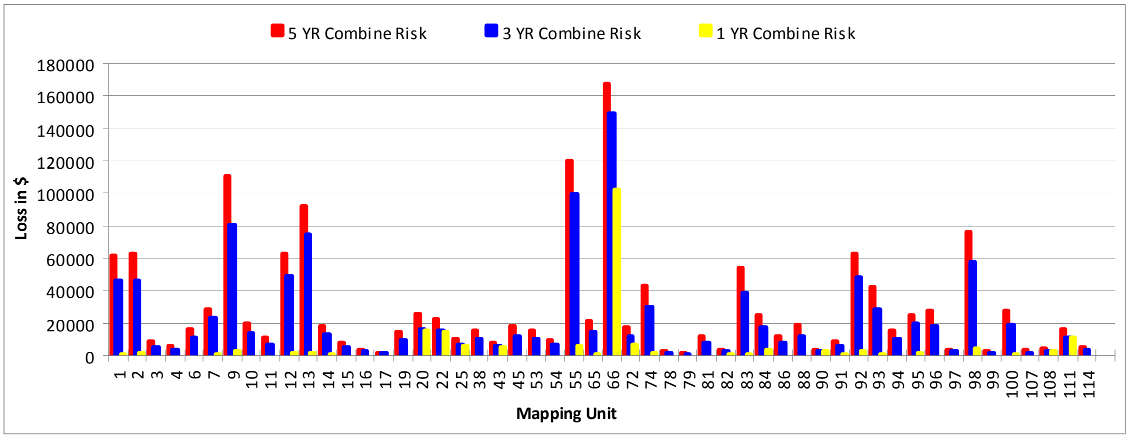

Figure 5-20 showing the histogram for all the final risk ($) obtained for two wheeler, four wheeler, big vehicles and road 1yr, 3yr and 5yr return period in different mapping units

(i.e. two wheelers, four wheelers, big vehicles and road) was observed in unit 66th of the study area as shown in (Fig 5-19), i.e. 170000 $ for 5yr return period, 150000 $ for 3yr return period and 105000 $ for 1yr return period, because of the high hazard probability for debris slide magnitude III in this unit.

6. Conclusions

6.1. Conclusions

Landslides are natural processes which have a high uncertainty with respect to their time and place of occurrence and their expected volumes and types. During the preparation of the landslide inventory from 1994 to 2008 it was observed that almost all the years have landslide occurrences on this particular road stretch except for the years 1999, 2001 and 2005.A total of 178 landslide locations were observed during the preparation of the inventory, in which the occurrence of rock slides was found in 140 locations and debris slides were found in 38 locations. Division of the terrain into different mapping units gave the overall surface observation of different landslides in the terrain i.e. on which face? or which slope? or in what type of terrain? the landslides have more occurrence. Separation of two types of landslides into 6 distinct magnitudes revealed a higher number of rock slides with magnitude II while the lowest was observed for debris slides with magnitude I. Hazard assessment in this study was done for 18 scenarios on the basis of two types of landslide (i.e. rock and debris slide), three type of magnitude for individual landslides type in 1yr, 3yr and 5yr return period. This estimation was done for smaller return period because higher return periods show a probability of 1 for maximum slides. Hazard assessment of landslide phenomenon was controlled by two components i.e. spatial probability and temporal probability. It was observed that the landslide hazard for magnitude III slides have the highest value of all categories of slides in this study. Landslide susceptibility for debris slide magnitude I is very low due to the limited number of landslides which was not found in BRO records and neither they are interpreted from the images. The hazard for rock slide magnitude III shows the highest value in the area. It can be concluded that the landslide hazard in this study is controlled by temporal probability of landslides, also area of the landslide to the area of the mapping unit which determines the degree of spatial probability in this study. The vulnerability estimation was based on traffic information of different vehicles i.e. two wheelers, four wheelers and big vehicles and expected number of different vehicles on different sections of the road which contain landslides and the vulnerability of road was calculated in the basis of the length of the road that might be damaged and cost for making a new road. For vehicle vulnerability it was concluded that number of two wheelers was maximum as compared with four wheelers and big vehicles which is due to the easy handling and affordable cost without considering the people inside different vehicles. High vulnerability was found for two wheelers as compared with four wheelers and big vehicles with increase in magnitude of landslide on the road corridor. Vulnerability to the road was found to be maximum in case of rock slide magnitude III and debris slide magnitude III in this study which was due to the higher magnitude of landslide and direct impact of landslides on the road. Direct risk was estimated for the road and the vehicles on the road with respect to different magnitude type of landslides. Risk of different vehicles increases with increase in magnitude of the landslides. Direct risk for different vehicles due to all magnitudes of debris slide was found to be 70000 $ which is lower than the values for all magnitudes of rock slides i.e. 245000 $. Direct risk of road was found to be 2100000 $ due to rock slide which was quite high than the direct risk of road due to debris slide i.e.543628 $.The higher value was due to the dominancy of rock slide magnitude II over other slides in the study area. Total risk of all vehicles and road was also higher for rock slide than debris slide, which is because of the higher frequency of rock slide in this study. Indirect risk in this study was calculated on the basis of road blockage time and loss of profit to various business types in Gangnani, Harsil and Sukhi Top during peak season. From the analysis it was concluded that the highest value for indirect risk was observed in religious vendors for both the places due to higher profit done by these shops. It was also concluded that the value of indirect risk also increase with increase in magnitude of landslide because higher magnitude of landslide release more materials which was take more time for removal. The lowest value of indirect risk was observed for sweets shops in Gangnani and Liquor shop in Harsil and Sukhi Top respectively, because of these shops are less in numbers and low profit income. Overall indirect risk was very much high for Harsil and Sukhi top than Gangnani, which is because of the high concentration of shops in Harsil and Sukhi Top. Finally it was observed that the 66th portion of the road section is having highest risk for different vehicles and road, which was due to the high hazard probability in this particular road section. It was found that in this section the occurrence of debris slide magnitude III was maximum, so for this section prior remedial measures should be taken, by stabilization of slopes or spreading sheets on the crown area.

6.2. Limitations in the study

- Estimation of temporal probability was only for small return period.
- Limited information on indirect risk for higher areas.
- Unknown historic damage so very difficult to validate.
- Dynamic elements of risk area not comprehensibly addressed.
- Quantitative susceptibility was not carried out because time limitation for the study.

6.3. Recommendations

- For estimating quantitative risk a long term observation of different elements at risk should be done.
- Use of probabilistic model for estimating the spatial probability is highly required for estimation of quantitative risk.
- Vulnerability estimation of dynamic elements should be done by using a stochastic modelling.
- As landslide occurrences are discrete phenomenon rainfall threshold modelling can reduce the uncertainty of the event.
- For validation of risk maps damage records or landslide records should be maintained properly.

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8. Appendices

Appendix 1-A: Details of Landslide occurrences obtained from BRO

YEAR	TYPE	FREQUENCY	LOCATION
1998, 2008	ROCK SLIDE	2	57.1
1998	DEBRIS SLIDE	3	57.2
2008	ROCK SLIDE	1	57.35
1998	ROCK SLIDE	2	57.4
2004	ROCK SLIDE	1	57.7
2000, 2004	ROCK SLIDE	2	58
2008	ROCK SLIDE	1	58.25
2000	ROCK SLIDE	1	58.8
1998, 2006	ROCK SLIDE	2	58.9
2000, 1994	ROCK SLIDE	3	59
1994, 1998	ROCK SLIDE	3	59.5
1998	ROCK SLIDE	1	59.7
1994	ROCK SLIDE	5	59.85
2008	DEBRIS SLIDE	1	60.15
1998, 2008	ROCK SLIDE	2	60.2
1994	ROCK SLIDE	5	60.25
1996	ROCK SLIDE	1	60.3
1994, 1995, 1996, 1998, 2008	DEBRIS SLIDE	18	60.5
1994, 2000	ROCK SLIDE	5	61.1
1994	DEBRIS SLIDE	2	61.3
2008	ROCK SLIDE	5	61.5
2006	ROCK SLIDE	1	61.55
2007	ROCK SLIDE	1	61.7
1998	ROCK SLIDE	2	61.9
1996	ROCK SLIDE	2	62
1994	ROCK SLIDE	2	62.05
1998	ROCK SLIDE	4	62.1
1995	ROCK SLIDE	1	62.15
1995	DEBRIS SLIDE	1	62.3
1994, 2003	ROCK SLIDE	4	62.4
1994	DEBRIS SLIDE	2	62.5
1995	DEBRIS SLIDE	6	62.6
1998	ROCK SLIDE	4	62.7
2008	ROCK SLIDE	2	62.9
2008	ROCK SLIDE	1	63
2006	ROCK SLIDE	1	63.1

Appendix 1-B: Details of Landslide occurrences obtained from BRO

YEAR	TYPE	FREQUENCY	LOCATION
1994	ROCK SLIDE	7	63.4
1994	ROCK SLIDE	2	63.5
2008	ROCK SLIDE	2	63.7
1994, 1995, 2008	ROCK SLIDE	6	63.8
2007	ROCK SLIDE	1	63.9
1994	ROCK SLIDE	4	64.2
1995	ROCK SLIDE	1	64.3
2007	DEBRIS SLIDE	1	64.5
2004, 2006	DEBRIS SLIDE	2	64.6
2003	ROCK SLIDE	1	64.9
1994	ROCK SLIDE	1	65.1
2006	ROCK SLIDE	2	65.15
2007, 2008	ROCK SLIDE	2	65.2
1994	ROCK SLIDE	3	65.3
2006	ROCK SLIDE	1	65.35
2000	ROCK SLIDE	1	65.4
1994	ROCK SLIDE	2	65.5
2008	ROCK SLIDE	2	65.8
2008	ROCK SLIDE	2	66.1
2006	ROCK SLIDE	1	66.15
2006	ROCK SLIDE	4	66.3
2006	ROCK SLIDE	1	66.4
2006	ROCK SLIDE	1	66.44
2006	ROCK SLIDE	3	66.48
2006	DEBRIS SLIDE	1	66.6
2006	ROCK SLIDE	1	66.75
2006	ROCK SLIDE	3	66.8
2006	ROCK SLIDE	1	66.9
2006	ROCK SLIDE	2	67
2006	ROCK SLIDE	2	67.2
2006	ROCK SLIDE	1	67.3
2006	ROCK SLIDE	2	67.4
2006	ROCK SLIDE	5	67.45
2006	ROCK SLIDE	1	67.5
2006	ROCK SLIDE	1	67.6
2006	DEBRIS SLIDE	5	67.8

Appendix 2-A: Details of specific risk obtained for Debris slide I for two wheeler, four wheeler and big vehicles

Specific Risk ($) of two wheeler for Debris Slide Magnitude I			
Mapping unit	**I year return period**	**3 year return period**	**5 year return period**
72	0.61	1.30	1.61
Specific Risk ($) of four wheeler for Debris Slide Magnitude I			
Mapping unit	**I year return period**	**3 year return period**	**5 year return period**
72	13.33	28.26	34.97
Specific Risk ($) of big vehicles for Debris Slide Magnitude I			
Mapping unit	**I year return period**	**3 year return period**	**5 year return period**
72	16.55	35.08	43.40

Appendix 2-B: Details of specific risk obtained for Debris slide II for two wheeler, four wheeler and big vehicles

Specific Risk ($) of two wheeler for Debris Slide Magnitude II			
Mapping unit	**I year return period**	**3 year return period**	**5 year return period**
20	3.74	10.51	16.43
22	8.38	22.13	32.67
25	2.09	5.86	9.17
43	7.17	17.85	25.01
66	37.82	80.16	99.18
72	6.62	17.48	25.79
90	1.73	4.86	7.60
108	0.82	2.31	3.62
111	3.12	8.25	12.17
Specific Risk ($) of four wheeler for Debris Slide Magnitude II			
Mapping unit	**I year return period**	**3 year return period**	**5 year return period**
20	101.79	286.12	447.43
22	219.03	578.45	853.75
25	56.40	158.53	247.92
43	192.11	478.16	669.91
66	932.89	1977.41	2446.72
72	157.29	415.41	613.11
90	45.93	129.09	201.87
108	21.96	61.72	96.53
111	84.89	224.21	330.91
Specific Risk ($) of big vehicles for Debris Slide Magnitude II			
Mapping unit	**I year return period**	**3 year return period**	**5 year return period**
20	124.13	348.90	545.62
22	278.30	735.00	1084.79
25	69.24	194.63	304.36
43	238.16	592.79	830.50
66	1256.06	2662.41	3294.29
72	219.83	580.58	856.89
90	57.44	161.46	252.48
108	27.33	76.83	120.15
111	103.67	273.81	404.12

Appendix 2-C: Details of specific risk obtained for Debris slide III for two wheeler, four wheeler and big vehicles

Specific Risk ($) of two wheeler for Debris Slide Magnitude III			
Mapping unit	**I year return period**	**3 year return period**	**5 year return period**
66	156.45	258.33	278.90
84	4.78	13.43	21.01
Specific Risk ($) of four wheeler for Debris Slide Magnitude III			
Mapping unit	**I year return period**	**3 year return period**	**5 year return period**
66	3520.41	5812.99	6275.84
84	107.26	301.50	471.49
Specific Risk ($) of big vehicles for Debris Slide Magnitude III			
Mapping unit	**I year return period**	**3 year return period**	**5 year return period**
66	5265.48	8694.50	9386.79
84	160.85	452.12	707.02

Appendix 2-D: Details of specific risk obtained for Rock slide I for two wheeler, four wheeler and big vehicles

Specific Risk ($) of two wheeler for Rock Slide Magnitude I			
Mapping unit	**I year return period**	**3 year return period**	**5 year return period**
16	1.39	3.91	6.11
65	2.71	6.04	7.74
72	0.73	1.72	2.30
84	0.36	1.01	1.58
114	1.33	3.74	5.84
Specific Risk ($) of four wheeler for Rock Slide Magnitude I			
Mapping unit	**I year return period**	**3 year return period**	**5 year return period**
16	28.18	79.22	123.88
65	54.39	121.28	155.63
72	13.85	32.59	43.58
84	6.91	19.42	30.38
114	31.84	89.48	139.94
Specific Risk ($) of big vehicles for Rock Slide Magnitude I			
Mapping unit	**I year return period**	**3 year return period**	**5 year return period**
16	39.56	111.21	173.91
65	77.27	172.31	221.10
72	21.38	50.29	67.26
84	10.41	29.26	45.76
114	37.72	106.04	165.82

Appendix 2-E: Details of specific risk obtained for Rock slide II for two wheeler, four wheeler and big vehicles

Specific Risk ($) of two wheeler for Rock Slide Magnitude II			
Mapping unit	**I year return period**	**3 year return period**	**5 year return period**
1	41.18	96.88	129.56
2	71.40	167.97	224.62
3	4.42	12.44	19.45
4	3.19	8.95	14.00
6	8.04	21.23	31.34
7	34.74	70.19	84.12
9	49.76	123.86	173.53
10	11.38	30.05	44.36
11	7.73	21.72	33.97
13	76.53	162.21	200.70
14	43.75	108.90	152.57
15	4.81	13.53	21.16
17	2.35	6.59	10.31
19	9.45	26.57	41.56
38	9.05	25.43	39.76
45	12.35	32.60	48.12
53	14.30	37.78	55.75
54	8.35	19.66	26.28
55	2.74	7.71	12.05
65	31.52	83.24	122.86
72	20.60	48.46	64.81
74	4.25	11.95	18.69
78	2.05	5.75	8.99
79	1.91	5.36	8.38
81	6.61	18.58	29.05
82	16.93	44.70	65.98
83	35.09	87.33	122.36
84	13.63	33.92	47.53
86	8.55	24.02	37.57
88	8.83	24.83	38.82
91	31.27	77.83	109.03
92	57.25	115.66	138.63
93	8.36	23.50	36.75
94	7.14	18.85	27.82
95	47.70	106.37	136.49
96	2.69	6.00	7.70
97	3.53	9.92	15.51
98	7.35	16.38	21.02
99	3.24	9.10	14.23
100	22.67	59.86	88.35
107	3.12	8.78	13.73
Specific Risk ($) of four wheeler for Rock Slide Magnitude II			
Mapping unit	**I year return period**	**3 year return period**	**5 year return period**
1	403.89	950.19	1270.67
2	757.44	1781.94	2382.96
3	43.84	123.22	192.69

4	31.54	88.65	138.63
6	79.08	208.85	308.25
7	338.93	684.74	820.74
9	508.88	1266.64	1774.57
10	112.89	298.13	440.02
11	76.43	214.84	335.96
13	755.82	1602.08	1982.30
14	428.23	1065.87	1493.30
15	47.24	132.79	207.65
17	22.83	64.17	100.35
19	93.07	261.61	409.11
38	89.19	250.69	392.04
45	119.54	315.72	465.98
53	139.97	369.66	545.58
54	81.43	191.56	256.18
55	29.06	81.67	127.72
65	313.54	828.06	1222.15
72	230.34	541.90	724.67
74	47.52	133.56	208.86
78	20.16	56.67	88.62
79	19.50	54.82	85.72
81	65.19	183.24	286.55
82	170.20	449.51	663.44
83	348.04	866.28	1213.66
84	296.81	738.78	1035.03
86	84.39	237.22	370.96
88	86.78	243.91	381.43
91	318.33	792.34	1110.07
92	620.02	1252.63	1501.42
93	85.40	240.04	375.37
94	68.48	180.87	266.94
95	494.93	1103.67	1416.20
96	26.13	58.26	74.76
97	35.70	100.36	156.94
98	83.69	186.63	239.47
99	32.39	91.04	142.37
100	226.30	597.66	882.10
107	30.23	84.96	132.87
Specific Risk ($) of big vehicles for Rock Slide Magnitude II			
Mapping unit	**I year return period**	**3 year return period**	**5 year return period**
1	615.07	1447.00	1935.04
2	1218.36	2866.30	3833.04
3	67.22	188.94	295.46
4	48.34	135.86	212.47
6	120.66	318.66	470.32
7	514.31	1039.08	1245.44
9	797.50	1985.02	2781.03
10	173.25	457.55	675.30
11	117.06	329.02	514.53
13	1156.48	2451.35	3033.13
14	651.21	1620.89	2270.88
15	71.98	202.32	316.38
17	34.58	97.21	152.02

19	142.09	399.40	624.58
38	136.31	383.14	599.16
45	180.49	476.69	703.55
53	212.82	562.07	829.57
54	123.48	290.49	388.47
55	46.71	131.28	205.30
65	482.08	1273.20	1879.14
72	385.26	906.35	1212.04
74	79.44	223.30	349.19
78	30.80	86.58	135.40
79	30.57	85.93	134.38
81	99.65	280.10	438.02
82	263.65	696.30	1027.69
83	534.09	1329.38	1862.47
84	484.53	1206.01	1689.62
86	129.12	362.93	567.55
88	157.36	442.32	691.70
91	497.34	1237.91	1734.31
92	1012.45	2045.48	2451.73
93	133.72	375.86	587.78
94	102.77	271.41	400.57
95	783.62	1747.42	2242.24
96	39.51	88.11	113.06
97	55.54	156.10	244.11
98	142.02	316.69	406.37
99	49.99	140.52	219.75
100	348.83	921.27	1359.72
107	45.63	128.25	200.55

Appendix 2-F: Details of specific risk obtained for Rock slide III for two wheeler, four wheeler and big vehicles

Specific Risk ($) of two wheeler for Rock Slide Magnitude III			
Mapping unit	**I year return period**	**3 year return period**	**5 year return period**
9	50.98	119.94	160.40
12	59.99	133.78	171.67
55	206.34	416.87	499.67
74	50.81	126.47	177.19
92	28.37	74.91	110.57
93	30.63	80.89	119.39
96	9.25	26.00	40.67
98	120.73	284.03	379.83
Specific Risk ($) of four wheeler for Rock Slide Magnitude III			
Mapping unit	**I year return period**	**3 year return period**	**5 year return period**
9	483.92	1138.45	1522.43
12	541.91	1208.42	1550.62
55	2059.07	4160.00	4986.20
74	545.23	1357.11	1901.32
92	291.64	770.23	1136.79
93	290.24	766.53	1131.34
96	81.53	229.17	358.38
98	1329.31	3127.33	4182.11

Specific Risk ($) of big vehicles for Rock Slide Magnitude III			
Mapping unit	**I year return period**	**3 year return period**	**5 year return period**
9	838.69	1973.09	2638.58
12	920.20	2051.99	2633.06
55	3645.91	7365.92	8828.84
74	997.68	2483.29	3479.10
92	523.27	1381.97	2039.68
93	502.67	1327.56	1959.37
96	137.08	385.31	602.55
98	2462.61	5793.50	7747.53

Appendix 3-A: Details of specific risk obtained for Debris slide I for road in 1yr, 3yr and 5yr return period

Specific Risk $ of Road for Debris Slide Magnitude I			
Mapping unit	**I year return period**	**3 year return period**	**5 year return period**
72	19.32	40.95	50.67

Appendix 3-B: Details of specific risk obtained for Debris slide II for road in 1yr, 3yr and 5yr return period

Specific Risk of Road for Debris Slide Magnitude II			
Mapping unit	**I year return period**	**3 year return period**	**5 year return period**
20	5547.36	15591.87	24382.55
22	5244.74	13851.89	20444.34
25	2219.98	6239.66	9757.58
43	1882.22	4684.95	6563.67
66	14103.66	29894.81	36990.23
72	2042.01	5393.16	7959.90
90	770.84	2166.59	3388.12
108	869.29	2443.30	3820.83
111	4087.12	10794.51	15931.88

Appendix 3-C: Details of specific risk obtained for Debris slide III for road in 1yr, 3yr and 5yr return period

Specific Risk $ of Road for Debris Slide Magnitude III			
Mapping unit	**I year return period**	**3 year return period**	**5 year return period**
66	60556.54	99992.50	107954.49
84	2186.99	6146.93	9612.56

Appendix 3-D: Details of specific risk obtained for Rock slide I for road in 1yr, 3yr and 5yr return period

Specific Risk $ of road for Rock Slide Magnitude I			
Mapping unit	**I year return period**	**3 year return period**	**5 year return period**
16	753.22	2117.05	3310.64
65	1111.40	2478.37	3180.20
72	29.20	68.69	91.85
84	17.30	48.61	76.02
114	1100.41	3092.89	4836.66

Appendix 3-E: Details of specific risk obtained for Rock slide I for road in 1yr, 3yr and 5yr return period

Specific Risk $ of road for Rock Slide Magnitude II			
Mapping unit	**I year return period**	**3 year return period**	**5 year return period**
1	18660.44	43900.08	58706.81
2	17736.54	41726.54	55800.18
3	1851.71	5204.56	8138.89
4	1244.41	3497.65	5469.62
6	3973.71	10494.97	15489.79
7	10626.49	21469.02	25732.74
9	15755.95	39217.37	54944.02
10	4869.06	12859.68	18979.92
11	2349.80	6604.54	10328.17
13	33113.46	70188.90	86847.97
14	4159.33	10352.77	14504.36
15	1627.43	4574.18	7153.11
17	423.96	1191.61	1863.45
19	3159.36	8879.96	13886.47
38	3316.13	9320.58	14575.51
45	4208.38	11114.75	16404.54
53	3500.88	9246.18	13646.67
54	2723.86	6408.08	8569.42
55	521.15	1464.80	2290.65
65	3751.84	9908.99	14624.93
72	1653.03	3888.89	5200.54
74	757.29	2128.51	3328.56
78	604.85	1700.04	2658.52
79	322.56	906.60	1417.75
81	2597.20	7299.89	11415.57
82	476.99	1259.77	1859.32
83	14534.00	36175.87	50682.85
84	3296.14	8204.25	11494.26
86	2428.92	6826.92	10675.94
88	4081.18	11470.90	17938.18
91	1501.42	3737.12	5235.75
92	13198.72	26665.77	31961.56
93	787.05	2212.14	3459.34
94	3681.34	9722.79	14350.12
95	7388.66	16476.33	21142.09
96	1255.27	2799.19	3591.87
97	698.50	1963.26	3070.14
98	980.53	2186.53	2805.71
99	574.38	1614.39	2524.58
100	6498.67	17163.64	25332.25
107	681.84	1916.43	2996.91

Appendix 3-F: Details of specific risk obtained for Rock slide III for road in 1yr, 3yr and 5yr return period

Specific Risk $ of road for Rock Slide Magnitude III			
Mapping unit	I year return period	3 year return period	5 year return period
9	14710.08	34606.56	46278.75
12	20440.33	45580.89	58488.48
55	42463.37	85790.01	102827.81
74	9542.11	23750.80	33275.17
92	5968.38	15763.09	23265.13
93	8817.64	23288.27	34371.74
96	5136.24	14436.33	22575.52
98	19334.80	45486.56	60828.39

Appendix 4-A: Details of Indirect risk obtained for Debris slide I for shops in Gangnani

Indirect Risk for Debris Slide Magnitude I in $							
Mapping Unit	SS	NR	FS	RV	GS	VegS	VS
72	6.74	56.13	11.23	80.83	8.98	11.23	17.96

Appendix 4-B: Details of Indirect risk obtained for Debris slide II for shops in Gangnani

Indirect Risk for Debris Slide Magnitude II in $							
Mapping Unit	SS	NR	FS	RV	GS	VegS	VS
20	8.82	73.50	14.70	105.83	11.76	14.70	23.52
22	12.29	102.43	20.49	147.50	16.39	20.49	32.78
25	11.46	95.49	19.10	137.50	15.28	19.10	30.56
43	8.30	69.16	13.83	99.58	11.06	13.83	22.13
66	12.48	103.99	20.80	149.75	16.64	20.80	33.28
72	12.64	105.32	21.06	151.67	16.85	21.06	33.70
90	8.65	72.05	14.41	103.75	11.53	14.41	23.06
108	8.82	73.50	14.70	105.83	11.76	14.70	23.52
111	13.85	115.45	23.09	166.25	18.47	23.09	36.94

Appendix 4-C: Details of Indirect risk obtained for Debris slide III for shops in Gangnani

Indirect Risk for Debris Slide Magnitude III in $							
Mapping Unit	SS	NR	FS	RV	GS	VegS	VS
66	10.42	86.81	17.36	125.00	13.89	17.36	27.78
84	7.92	65.97	13.19	95.00	10.56	13.19	21.11

Appendix 4-D: Details of Indirect risk obtained for Rock slide I for shops in Gangnani

Indirect Risk for Rock Slide Magnitude I in $							
Mapping Unit	SS	NR	FS	RV	GS	VegS	VS
16	10.00	83.33	16.67	120.00	13.33	16.67	26.67
65	8.82	73.50	14.70	105.83	11.76	14.70	23.52
72	7.22	60.19	12.04	86.67	9.63	12.04	19.26
84	6.94	57.87	11.57	83.33	9.26	11.57	18.52
114	6.94	57.87	11.57	83.33	9.26	11.57	18.52

Appendix 4-E: Details of Indirect risk obtained for Rock slide II for shops in Gangnani

Indirect Risk for Rock Slide Magnitude II in $							
Mapping Unit	**SS**	**NR**	**FS**	**RV**	**GS**	**VegS**	**VS**
1	9.86	82.18	16.44	118.33	13.15	16.44	26.30
2	17.50	145.83	29.17	210.00	23.33	29.17	46.67
3	14.72	122.69	24.54	176.67	19.63	24.54	39.26
4	15.42	128.47	25.69	185.00	20.56	25.69	41.11
6	17.71	147.57	29.51	212.50	23.61	29.51	47.22
7	9.10	75.81	15.16	109.17	12.13	15.16	24.26
9	12.99	108.22	21.64	155.83	17.31	21.64	34.63
10	9.79	81.60	16.32	117.50	13.06	16.32	26.11
11	13.26	110.53	22.11	159.17	17.69	22.11	35.37
13	12.29	102.43	20.49	147.50	16.39	20.49	32.78
14	8.82	73.50	14.70	105.83	11.76	14.70	23.52
15	11.42	95.20	19.04	137.08	15.23	19.04	30.46
17	8.13	67.71	13.54	97.50	10.83	13.54	21.67
19	7.57	63.08	12.62	90.83	10.09	12.62	20.19
38	12.50	104.17	20.83	150.00	16.67	20.83	33.33
45	10.86	90.51	18.10	130.33	14.48	18.10	28.96
53	13.89	115.74	23.15	166.67	18.52	23.15	37.04
54	10.73	89.41	17.88	128.75	14.31	17.88	28.61
55	10.90	90.86	18.17	130.83	14.54	18.17	29.07
65	12.71	105.90	21.18	152.50	16.94	21.18	33.89
72	12.08	100.69	20.14	145.00	16.11	20.14	32.22
74	13.09	109.09	21.82	157.08	17.45	21.82	34.91
78	11.60	96.64	19.33	139.17	15.46	19.33	30.93
79	10.21	85.07	17.01	122.50	13.61	17.01	27.22
81	13.02	108.51	21.70	156.25	17.36	21.70	34.72
82	7.43	61.92	12.38	89.17	9.91	12.38	19.81
83	13.75	114.58	22.92	165.00	18.33	22.92	36.67
84	10.21	85.07	17.01	122.50	13.61	17.01	27.22
86	11.94	99.54	19.91	143.33	15.93	19.91	31.85
88	11.60	96.64	19.33	139.17	15.46	19.33	30.93
91	6.91	57.58	11.52	82.92	9.21	11.52	18.43
92	10.90	90.86	18.17	130.83	14.54	18.17	29.07
93	9.34	77.84	15.57	112.08	12.45	15.57	24.91
94	10.31	85.94	17.19	123.75	13.75	17.19	27.50
95	11.42	95.20	19.04	137.08	15.23	19.04	30.46
96	8.61	71.76	14.35	103.33	11.48	14.35	22.96
97	9.86	82.18	16.44	118.33	13.15	16.44	26.30
98	15.94	132.81	26.56	191.25	21.25	26.56	42.50
99	9.51	79.28	15.86	114.17	12.69	15.86	25.37
100	13.51	112.56	22.51	162.08	18.01	22.51	36.02
107	7.60	63.37	12.67	91.25	10.14	12.67	20.28

Appendix 4-F: Details of Indirect risk obtained for Rock slide III for shops in Gangnani

Indirect Risk for Rock Slide Magnitude III in $							
Mapping Unit	**SS**	**NR**	**FS**	**RV**	**GS**	**VegS**	**VS**
9	8.26	68.87	13.77	99.17	11.02	13.77	22.04
12	13.40	111.69	22.34	160.83	17.87	22.34	35.74
55	9.10	75.81	15.16	109.17	12.13	15.16	24.26
74	10.90	90.86	18.17	130.83	14.54	18.17	29.07
92	15.35	127.89	25.58	184.17	20.46	25.58	40.93
93	11.42	95.20	19.04	137.08	15.23	19.04	30.46
96	18.68	155.67	31.13	224.17	24.91	31.13	49.81
98	13.68	114.00	22.80	164.17	18.24	22.80	36.48

Appendix 5-A: Details of Indirect risk obtained for Debris slide I for shops in Harsil and Sukhi Top

Indirect Risk for Debris Slide Magnitude I in $									
Mapping Unit	**SS**	**NR**	**FS**	**RV**	**VS**	**GS**	**VegS**	**MS**	**LS**
72	333.44	606.25	306.49	1185.56	157.18	303.13	161.67	44.91	43.78

Appendix 5-B: Details of Indirect risk obtained for Debris slide II for shops in Harsil and Sukhi Top

Indirect Risk for Debris Slide Magnitude II in $									
Mapping Unit	**SS**	**NR**	**FS**	**RV**	**VS**	**GS**	**VegS**	**MS**	**LS**
20	436.56	793.75	401.28	1552.22	205.79	396.88	211.67	58.80	57.33
22	608.44	1106.25	559.27	2163.33	286.81	553.13	295.00	81.94	79.90
25	567.19	1031.25	521.35	2016.67	267.36	515.63	275.00	76.39	74.48
43	410.78	746.88	377.59	1460.56	193.63	373.44	199.17	55.32	53.94
66	617.72	1123.13	567.80	2196.33	291.18	561.56	299.50	83.19	81.11
72	625.63	1137.50	575.07	2224.44	294.91	568.75	303.33	84.26	82.15
90	427.97	778.13	393.39	1521.67	201.74	389.06	207.50	57.64	56.20
108	436.56	793.75	401.28	1552.22	205.79	396.88	211.67	58.80	57.33
111	685.78	1246.88	630.36	2438.33	323.26	623.44	332.50	92.36	90.05

Appendix 5-C: Details of Indirect risk obtained for Debris slide II for shops in Harsil and Sukhi Top

Indirect Risk for Debris Slide Magnitude III in $									
Mapping Unit	**SS**	**NR**	**FS**	**RV**	**VS**	**GS**	**VegS**	**MS**	**LS**
66	515.63	937.50	473.96	1833.33	243.06	468.75	250.00	69.44	67.71
84	391.88	712.50	360.21	1393.33	184.72	356.25	190.00	52.78	51.46

Appendix 5-D: Details of Indirect risk obtained for Rock slide I for shops in Harsil and Sukhi Top

Indirect Risk for Rock Slide Magnitude I in $									
Mapping Unit	**SS**	**NR**	**FS**	**RV**	**VS**	**GS**	**VegS**	**MS**	**LS**
16	495.00	900.00	455.00	1760.00	233.33	450.00	240.00	66.67	65.00
65	436.56	793.75	401.28	1552.22	205.79	396.88	211.67	58.80	57.33
72	357.50	650.00	328.61	1271.11	168.52	325.00	173.33	48.15	46.94
84	343.75	625.00	315.97	1222.22	162.04	312.50	166.67	46.30	45.14
114	343.75	625.00	315.97	1222.22	162.04	312.50	166.67	46.30	45.14

Appendix 5-E: Details of Indirect risk obtained for Rock slide II for shops in Harsil and Sukhi Top

Indirect Risk for Rock Slide Magnitude II in $									
Mapping Unit	**SS**	**NR**	**FS**	**RV**	**VS**	**GS**	**VegS**	**MS**	**LS**
1	488.13	887.50	448.68	1735.56	230.09	443.75	236.67	65.74	64.10
2	866.25	1575.00	796.25	3080.00	408.33	787.50	420.00	116.67	113.75
3	728.75	1325.00	669.86	2591.11	343.52	662.50	353.33	98.15	95.69
4	763.13	1387.50	701.46	2713.33	359.72	693.75	370.00	102.78	100.21
6	876.56	1593.75	805.73	3116.67	413.19	796.88	425.00	118.06	115.10
7	450.31	818.75	413.92	1601.11	212.27	409.38	218.33	60.65	59.13
9	642.81	1168.75	590.87	2285.56	303.01	584.38	311.67	86.57	84.41
10	484.69	881.25	445.52	1723.33	228.47	440.63	235.00	65.28	63.65
11	656.56	1193.75	603.51	2334.44	309.49	596.88	318.33	88.43	86.22
13	608.44	1106.25	559.27	2163.33	286.81	553.13	295.00	81.94	79.90
14	436.56	793.75	401.28	1552.22	205.79	396.88	211.67	58.80	57.33
15	565.47	1028.13	519.77	2010.56	266.55	514.06	274.17	76.16	74.25
17	402.19	731.25	369.69	1430.00	189.58	365.63	195.00	54.17	52.81
19	374.69	681.25	344.41	1332.22	176.62	340.63	181.67	50.46	49.20
38	618.75	1125.00	568.75	2200.00	291.67	562.50	300.00	83.33	81.25
45	537.63	977.50	494.18	1911.56	253.43	488.75	260.67	72.41	70.60
53	687.50	1250.00	631.94	2444.44	324.07	625.00	333.33	92.59	90.28
54	531.09	965.63	488.18	1888.33	250.35	482.81	257.50	71.53	69.74
55	539.69	981.25	496.08	1918.89	254.40	490.63	261.67	72.69	70.87
65	629.06	1143.75	578.23	2236.67	296.53	571.88	305.00	84.72	82.60
72	598.13	1087.50	549.79	2126.67	281.94	543.75	290.00	80.56	78.54
74	647.97	1178.13	595.61	2303.89	305.44	589.06	314.17	87.27	85.09
78	574.06	1043.75	527.67	2041.11	270.60	521.88	278.33	77.31	75.38
79	505.31	918.75	464.48	1796.67	238.19	459.38	245.00	68.06	66.35
81	644.53	1171.88	592.45	2291.67	303.82	585.94	312.50	86.81	84.64
82	367.81	668.75	338.09	1307.78	173.38	334.38	178.33	49.54	48.30
83	680.63	1237.50	625.63	2420.00	320.83	618.75	330.00	91.67	89.38
84	505.31	918.75	464.48	1796.67	238.19	459.38	245.00	68.06	66.35
86	591.25	1075.00	543.47	2102.22	278.70	537.50	286.67	79.63	77.64
88	574.06	1043.75	527.67	2041.11	270.60	521.88	278.33	77.31	75.38
91	342.03	621.88	314.39	1216.11	161.23	310.94	165.83	46.06	44.91
92	539.69	981.25	496.08	1918.89	254.40	490.63	261.67	72.69	70.87
93	462.34	840.63	424.98	1643.89	217.94	420.31	224.17	62.27	60.71
94	510.47	928.13	469.22	1815.00	240.63	464.06	247.50	68.75	67.03
95	565.47	1028.13	519.77	2010.56	266.55	514.06	274.17	76.16	74.25
96	426.25	775.00	391.81	1515.56	200.93	387.50	206.67	57.41	55.97
97	488.13	887.50	448.68	1735.56	230.09	443.75	236.67	65.74	64.10
98	788.91	1434.38	725.16	2805.00	371.88	717.19	382.50	106.25	103.59
99	470.94	856.25	432.88	1674.44	221.99	428.13	228.33	63.43	61.84
100	668.59	1215.63	614.57	2377.22	315.16	607.81	324.17	90.05	87.80
107	376.41	684.38	345.99	1338.33	177.43	342.19	182.50	50.69	49.43

Appendix 5-F: Details of Indirect risk obtained for Rock slide Iil for shops in Harsil and Sukhi Top

Indirect Risk for Rock Slide Magnitude III in $									
Mapping Unit	**SS**	**NR**	**FS**	**RV**	**VS**	**GS**	**VegS**	**MS**	**LS**
9	409.06	743.75	376.01	1454.44	192.82	371.88	198.33	55.09	53.72
12	663.44	1206.25	609.83	2358.89	312.73	603.13	321.67	89.35	87.12
55	450.31	818.75	413.92	1601.11	212.27	409.38	218.33	60.65	59.13
74	539.69	981.25	496.08	1918.89	254.40	490.63	261.67	72.69	70.87
92	759.69	1381.25	698.30	2701.11	358.10	690.63	368.33	102.31	99.76
93	565.47	1028.13	519.77	2010.56	266.55	514.06	274.17	76.16	74.25
96	924.69	1681.25	849.97	3287.78	435.88	840.63	448.33	124.54	121.42
98	677.19	1231.25	622.47	2407.78	319.21	615.63	328.33	91.20	88.92