Spatio-temporal Landslide Hazard Analysis along a Road Corridor based on Historical Information: A Case Study from Uttarakhand India

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by

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I certify that although I may have conferred with others in preparing for this assignment, and drawn upon a range of sources cited in this work, the content of this Thesis Report is my original work.

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Abstract

Slope failures are among the most frequent disasters experienced by the Himalayan terrains of India. Especially along the road corridors, connecting the remote mountainous destinations to the mainland the slope failures are observed to exert a noteworthy impact. These failures are mostly initiated as a consequence of human inference on the steep hill slopes. Therefore, with a little monsoonal or further anthropogenic trigger, these slopes are subjected to experience frequent slips each year.

This research aims to understand the landslide hazard scenario from both spatial and temporal aspects. One of the famous road corridors (NH 108), along the river Bhagirathi, connecting the Gangotri shrine to Uttarkashi is taken for the testing of spatio-temporal landslide hazard model. According to the proposed methodology, the road corridor of interest was segmented into 41 sections as unique conditions units on the basis of slope and underlying lithology, as per the ESRI (GIS) concepts. Extremely rugged terrain condition induces very deep shadow over the road in the satellite image which consequently hides the road details in several places. This limitation is supplemented by generation of road layer with GPS tool with all required details for producing hazard scenarios at a large scale. An historical approach was adopted for generation of temporal landslide database. Further remote sensing tool was used to obtain the spatial database of landslides. Combination of several means and methods like collection of historic records on landslides, remote sensing imageries, GIS and GPS are altogether implemented to construct a spatio-temporal landslide database for the road corridor (NH 108) for past 25 years. An intensive field study was carried out for validation of historic records of slides along the road corridor. In addition to that landslides are grouped into several types on the basis of field observations following the major landslide classification scheme.

The temporal database was used to derive the number of landslides occurrences in each road unit. Therefore the exceedance probability of one or more landslides was calculated for each road unit for one year, five years and ten years time periods. The landslides density over the road corridor was obtained from the spatial database of slides and further spatial probability was derived in terms of ratio of slide density in each unit and density in entire road corridor. The joint probability of landslide hazard was derived as a product of temporal and spatial probabilities. Finally the predicted temporal and spatial probability was assessed at each failure for different time periods for validation of the adopted methodology which has produced satisfactory results. The relationship between frequency and length of landslides affecting the road corridor was verified which showed 82.8% of the slides occurred in past 25 years have a length between 10 to 40 meters while only 6% of the slides have a length of more than 60 meters along the road stretch.

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1. Introduction:

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 in the Himalayas. In mountainous terrain landslides are natural degradational processes and major landscape development factors as well. Weak geological structure, steep and rugged surface, high altitude variation along with monsoon triggers give rise to high degree of fragility in the whole mountain system. Even over these fragile parcels of land surfaces huge number of human population is residing and adapting a typical socioeconomic procedure which is rather an example of risky and hard lifestyle than the people residing in rest part of the world. Along with this there is an unfortunate coincidence of vulnerable, poor population, limited availability of recourses and unstable landscape result in worse situation in terms of socioeconomic damage whenever any landslide event takes place over these surfaces.

Landslides in its strict sense are the movement of a mass of rock, debris or earth down slope, due to gravitational pull, and in general are triggered by a variety of external factors such as intense rainfall, earthquake shaking, water level change, storm waves and rapid stream erosion etc (Dai et al., 2002).These triggering factors have an influence in increasing the shear stress and decreasing shear strength of slope forming materials beyond a threshold limit and cause failure. In addition to that, extensive human interference in the hill slope areas for construction of roads, urban expansion along the hill slopes, deforestation, rapid change in land use etc contribute as one of the most significant anthropogenic factors to instability. A variety of movements are associated with landslides flowing, sliding, toppling or falling movements, and many landslides exhibit a combination of two or more types of movements (Varnes, 1978; Cruden and Varnes, 1996;). Landslides exhibit it self in a range of different mass movement processes and is considered among the most complex natural hazards occurring on the surface of earth. The extraordinary breadth of the spectrum of landslide phenomena makes it difficult – if not impossible – to define a single methodology to identify and map landslides, to ascertain landslide hazards, and to evaluate the associated risk (Guzzetti, 2005).

1.1. Problem Identification:

In the Himalayan region of India land degradation is mainly caused by landslides and have become an annually recurring phenomena. Especially in Garhwal Himalaya these events are reported very often. Economically this part of the world is not stable enough and thrives on tourism and pilgrimage. Very high altitude, rugged terrain (relative relief around 600m), less agricultural land, extreme environmental conditions and lesser amount of industrial development restrict the economy to flourish at its full extent. Thus frequent landslides are one of the greatest threats for the fragile economy of this mountainous terrain. The problem of landslides becomes more aggravated especially during monsoon season though the main causative factors behind the instability of landsurface are mainly geomorphologic and geological in nature .Frequent seismic events also play a major role in inducing such a large number of landslide events in Garhwal Himalaya. Existence of several thrust faults causes large number of tectonic events, consequently gives rise to various landslide incidents.

The history of Uttarakhand is well familiar with landslip events. In the year 1998 more than 300 people were killed including 60 pilgrims in Kailas-Manasarover due to Malpa landslide in Uttarakhand (The Hindu., 1998). Landslides induced by earthquake shocks again spread devastation in the year 1999 in Chamoli district of Uttarakhand (kimothei., et al, 2005). The 20th October 1991 the Uttarkashi Earthquake caused numerous massive landslides, particularly on a 42 km road stretch between Uttarkashi and Bhatwari (Jain et al, 1992) and Varunavat Parvat landslide in Bhagirathi valley Uttarkashi (Gupta and Bist., 2004; Sarkar and Gupta., 2005) are few examples of gigantic landslides in Bhagirathi river valley . On 16 July 2001, heavy rainfall due to cloudburst in Phata Byung area of Rudraprayag district, Uttaranchal, triggered more than 200 landslides and killed 27 people (Kumar et al., 2003). Normal life in this area was severely affected by these slides. A week of disaster between 11 and 19 August in 1998 was found in the history of Ukhimath area in Garhwal Himalaya in which the landslides occurred in two phases along the lower catchments of the Madhmaheswar and Kaliganga Rivers affected 20 km^2 of area. It took lives of 103 persons (Naithani et al., 2002). Thus it becomes necessary to mitigate the disastrous impact with a detail understanding of the physical process and sufficient amount of historical information quantifying the hazard with both temporal and spatial approaches.

As this area is very much important from a tourism point of view and landslide events along the roads completely cut off the supply line of various dispersed hill stations and make it isolated from the rest part of the country, the hazard zonation in terms of spatial probability along the communication route is less sufficient to deal with the problem. Therefore it is necessary to take into account the temporal aspect of landslide hazard in order to carry out a complete quantitative assessment of the phenomenon.

Most of the landslide studies have been attempted in order to find out the spatial susceptibility but the areas which are already prone to landslide or highly susceptible and landslide events are very frequently observed and recorded, particularly in those areas the assessment of temporal hazard rate can be more beneficial and can produce more significant hazard scenarios and further studies can help in carrying out the a quantitative assessment of vulnerable elements at risk as well.

This particular research is an attempt towards detecting the potential and actual landslide prone areas and analyzing the probability of occurrence of landslide in spatiotemporal domain in order to derive a rather comprehensive hazard scenario with the help of available historic records of landslides. The adapted methodology is an effort in determining the temporal hazard rate of landslide in a large scale without the utilization of multi-temporal remote sensing products.

1.2. Objectives:

To develop a methodology for the determination spatial and temporal probability of landslides of a road corridor in the Himalayas based on historical landslide records.

1.2.1. Sub-Objectives:

- Preparation of a detail temporal landslide inventory of the road corridor National Highway 108.

- Division of the route corridor into homogeneous geo-environmental mapping units in order to find out temporal probability of sliding of different spatial units.

- Development of a methodology for quantitative landslide hazard assessment along a strategic road corridor.

1.3. Research Questions:

1.3.1. Questions pertaining to main and first sub objective:

- Is it possible to obtain sufficiently detailed historical landslide information based on registers from the Border Road Organisation?

- What are the historical information required and in what format is to be collected as well as arranged in order to carry out a temporal hazard analysis along the route corridor?

- Can the landslides reported by BRO be linked to evidences of past landslides in the field?

- How many landslides in the study area are fresh and reactivated?

1.3.2. Questions pertaining to second sub objective:

- What will be the possible form of homogeneous spatial (mapping) units along the route corridor whose temporal hazard rate will be predicted?

1.3.3. Questions pertaining to third sub objective:

- How to assess the spatial probability?

- How to assess the temporal landslide probability?

- How to combine the spatial and temporal probability values in order to derive a quantitative landslide hazard map?

- Is there a relation between frequency and magnitude possible?

1.4. Overview of Adapted Methodology:

In order to predict the temporal hazard rate of landslides in GIS environment the following methodology mainly based on historic information is being adapted.

1.4.1. Methodology Flow Chart:

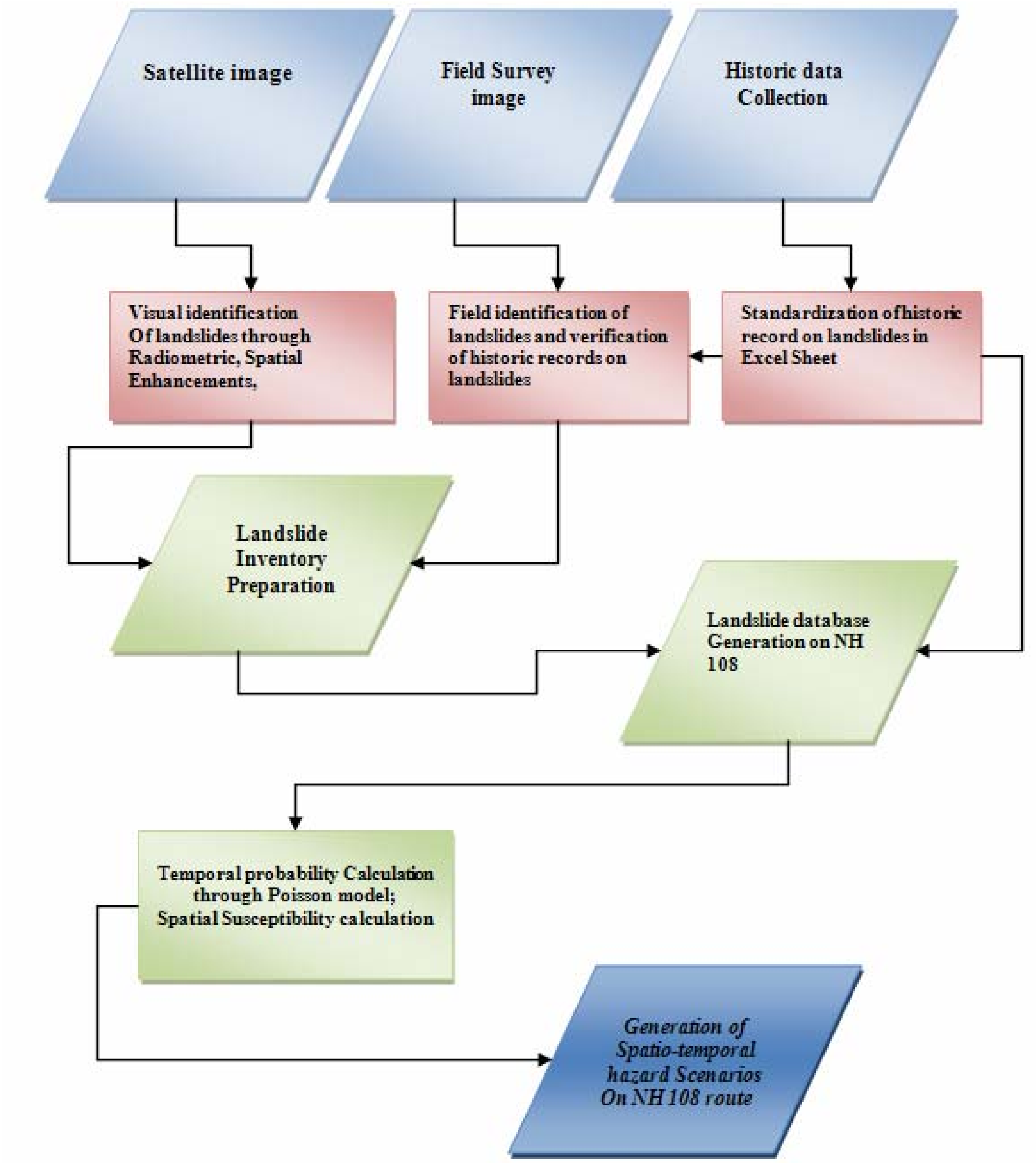


Figure 1.1: Showing the methodology of steps adapted for the research.

2. Literature Review:

The chapter provides a review on the literature study done to obtain an understanding of various components of landslide hazard studies. It reviews the different literatures providing the definitions related to the term landslides itself followed by it classification types and possible causes of initiation of such a hazardous phenomenon in and around us. The chapter also reviews the different approaches adapted for quantification of landslide hazard from different domain and possible combinations determining rather significant hazard scenarios.

2.1. Hazard:

Hazard by its definition is the "probability of occurrence of a potentially damaging phenomenon within a specified period of time and within a given area" (Varnes, 1984). The term "magnitude" is amended to include in the definition by (Guzzetti., et al, 1999). According to the literatures available, the hazards are mainly the expressions of both ongoing natural and human activities on this surface of earth, thus can be differentiated in to natural and human induced hazards. landslides are considered as "Geological Hazards" (UNESCO, 1997) while sometimes the term" flood" is also used for describing a fast flow type phenomenon occurring over slopes. Thirteen predominant hazards types are identified by UNESCO. Further four basic types of hazards are suggested in different literatures such as geological hazard, hydro meteorological hazard and biological hazard (UNDP, 2004).

Geological Hazards	Climatic Hazards	Environmental Hazards
1. Earthquakes 2. Tsunami 3. Volcanic eruptions 4. Landslides	5. Tropical cyclones 6. Floods 7. Drought	8. Environmental pollution 9. Deforestation 10. Desertification 11. Pest Infestation
12. Epidemics	13. Chemical and Industrial Accidents	

Figure 2.1 Types of Hazards according to (UNESCO 1997)

2.2. Landslides:

The term "landslide" describes a 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 which are basically different forms of mass wasting process active over landsurface. It is kind of "gravitative transfer producing immediate and perceptible modification of earth's surface" (Thornbury, 1954). The most popular definition of landslides is given as the "the movement of a mass of rock, debris, or earth down a slope (Cruden, 1991) which encompasses different sort of slope failure processes observed in nature. These huge varieties of landslides present in nature involves a definite criteria for classification of slides

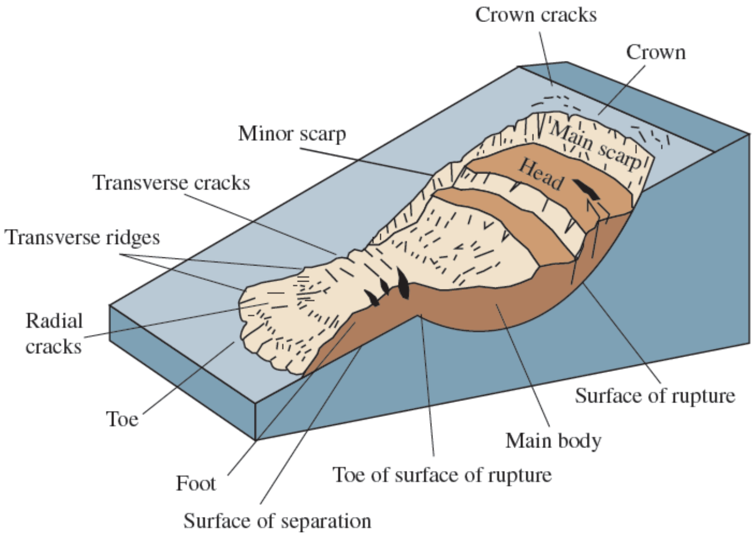


Figure 2.2: Showing the general morphology of an ideal landslide (USGS, 2006)

Varnes, 1978 emphasised on the inclusion of parameters like type of movement and type of material displaced while classifying the slides. Sliding involves a continuous contact of the moving mass with surface while fall denotes loss of contact of the moving mass with surface. On the other hand flow is a continuous movement of weathered material accompanied by surface water which rather is responsible for the initiation of the movement.

TYPE OF MOVEMENT		TYPE OF MATERIAL		
		BEDROCK	ENGINEERING SOILS	
			Predominantly coarse	Predominantly fine
FALLS		Rock fall	Debris fall	Earth fall
TOPPLES		Rock topple	Debris topple	Earth topple
SLIDES	ROTATIONAL	Rock slide	Debris slide	Earth slide
	TRANSLATIONAL			
LATERAL SPREADS		Rock spread	Debris spread	Earth spread
FLOWS		Rock flow (deep creep)	Debris flow	Earth flow
			(soil creep)	
COMPLEX		Combination of two or more principal types of movement		

Table 2.1: showing the classification scheme of landslides after (Cruden and Varnes, 1996)

Landslides can be further grouped in to several types related to its age (Cruden and Varnes, 1996). Regarding the age of slides or its state of activity , distribution and style they are differentiated as active, reactivated, suspended, inactive; advancing, retrogressive, widening, enlarging confined, diminishing, moving; complex, composite, multiple, successive and single respectively. This variety of classification is adapted for comprehensive investigation of such a complex natural process which is essentially an endeavour in the direction of constructing a useful database as a foundation of expert system of landslide mitigation.

2.3. Landslide identification and mapping:

Landslide mapping is the preliminary step towards landslide hazard studies. It is done to obtain different landslide inventory maps those generally serve as the raw material for producing various hazard seniors. Accurate mapping of a landslide in terms of magnitude is still a challenge to scientific community and therefore enormous scope of research is lying in finding out both the manual and automated way of accurate and précised identification as well as mapping.

2.3.1. Landslide Inventories:

An accurate landslide inventory is a prerequisite for any kind of landslide hazard studies irrespective of models and methods (Varnes, 1984). The most straightforward type of hazard map is a landslide inventory map (Westen, 1993). These inventories are the simple form of landslide maps (Hansen, 1984; Wieczorek, 1984; Guzzetti et al., 1999). An inventory map records the location and, when known, the date of occurrence and types of landslides that have left discernible traces in an area (Malamud et al., 2004). Guzzetti (2005) proposed that the major assumptions for identification and mapping of landslides can be: 1) Landslides leave typical signatures on the terrain surface, i.e., they refer to changes in the form, position or appearance of the topographic surface, 2) the morphological signature left by a landslide can be interpreted to determine the extent of the slope failure and to infer the type of movement (e.g., fall, flows, slides, complex, compound etc.) and the rate of movement, 3) landslides are controlled by many terrain factors, and are a combined result of the interplay of physical processes and mechanical laws that can be determined empirically, statistically or in deterministic fashion, 4) landslide occurrence follows the principle of uniformitarianism. According to (Carrara et all., 1995) the spatial distribution of past (relict) and recent landslides is the key for predicting slope movements in advance. Thus the landslide studies are generally carried out on the basis of these assumptions.

Landslide inventories can differ according to the purpose of the study and procedure followed to generate the inventory. Geomorphological inventory maps ; a landslide-event inventory, associated with all the slope failures caused by a single trigger, such as an earthquake, rainstorm or snowmelt, a historical landslide inventory; the sum of many landslide events over a period of tens, hundreds or even many thousands of years (Malamud et al., 2004).

2.3.2. Inventory generation tools:

A variety of tools are available for generation of both event based and historical landslide inventories. On the basis of collected historic records on location of of slides occurred and their dimension, they can be mapped with in GIS environment. Further new attributes can be added to prepare a historic landslide database with the help of GIS and various query language softwares available, enabling in running some advance sort of queries for an expert system analysis. The methodology included research of historical sources at national institutions, public libraries, international journals, the Internet, and the collection of original texts from newspapers and their transcription in analogue format. Though such records contain some exaggerations but still provide a fairly good detail of temporal aspect of the event (Devoli et al., 2006).

Digital remote sensing products are proved to be beneficial in mapping landslides in remote and inaccessible areas due to high resolution (Jaiswal, 2007). Interpretation of monoscopic and stereoscopic images helps in identification and characterization of landslides as a fact of its ability of providing spectral information as well as three dimensional perspectives. Mainly because of its synoptic view and its capability for repetitive observations, optical (visible-infrared) remotely sensed imagery acquired at different dates and at high spatial resolution can be considered as an effective complementary tool for field techniques to derive such information (Hervas, et al., 2003).

But in inaccessible terrain it is always a challenge to carry out landslide mapping (Das, 2007). In rugged forested watershed, canopy cover camouflages the small landslides to a great extent and detecting all landslides from images is a difficult task (Bradinoni et al., 2003). Therefore it will be relevant to suggested that construction of landslide inventory requires a combination of several means and methods to be followed.

2.4. Approaches to landslide hazard zonation:

Landslide Hazard Zonation (LHZ) refers to "the division of a land surface into homogeneous areas or domains and their ranking according to degrees of actual, potential hazard caused by mass-movement (Varnes, 1984). But in practice LHZ is often attempted in terms of spatial susceptibility only. Those susceptibility maps typically aim to predict “where” failures are likely to occur without any clear indication of “when” or “how big or small” they will be. Where as an ideal slope instability hazard map should provide the information on the spatial probability, temporal probability, type magnitude, velocity, run out distance of the mass in movement (Westen, 1993).

2.4.1. Spatial landslide hazard (susceptibility)

Spatial susceptibility maps portraying the probability of occurrences of similar phenomena in future are derived by means of several methods. These are broadly classified as direct and indirect methods. The direct method consists of geomorphological mapping in which past and present landslides are identified and assumptions are made on the factors leading to instability, after which a zonation is made of those sites where failures are most likely to occur. The indirect method includes two different approaches, namely the heuristic (knowledge driven) and statistical (data driven) techniques (Carrara et al., 1995). In the heuristic approach, 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 mass movements. This is normally based on‘priori’ knowledge available to experts on various causes of landslides in the area of investigation.

In the statistical approach, the probability values are determined based on the relationship with the past/present landslide distribution. The statistical techniques used in landslide susceptibility mapping are: discriminant analysis (Carrara et. al. 1991), multivariate statistics, Bayesian conditional analysis like weights of evidence method (Lee., et al. 2002;), likelihood ratio (Chung and Fabri, 2005; Fabri et al. 2003;).One of simplest but effective method was proposed by (Yin and Yan 1988) information value, mainly based on prior probability and has been attempted several times for calculation of hazard probabilities of different factors causing instability.

Fuzzy set theory formulated by Zadeh (1965) differs from the traditional Boolean set theory is also used for landslide hazard studies (Champati ray., 1996). This is basically a semi-quantitative approach where traditional set, an object is completely in either the set (degree of membership is 1), or it is not in the set at all (degree of membership is 0). The degree to which an object is a member of a fuzzy set can have any value between 0 and 1, rather than strictly 0 or 1 as in a traditional set. Mathematically, a fuzzy set S is defined as a set of ordered pairs: This membership function is also interpreted as "possibility function". Fuzzy membership values, can be combined by using standard rules of fuzzy algebra to combine number of exploration data sets, Zimmermann (1985) has discussed five such operators, namely the fuzzy AND, the fuzzy OR, fuzzy algebraic product, fuzzy algebraic sum and fuzzy gamma operator. The most important one is the fuzzy gamma operator which was proposed by Zimmermann and Zysno (1980) and which gives a value between fuzzy algebraic sum and fuzzy algebraic product operator. The choice of gamma value influences in the final results. A gamma value of 1 implies full compensation while gamma value of 0 denotes no compensation.

With the advancement of computing technology, it has become feasible to apply various statistical methods to analyze landslide phenomena and derive at reproducible hazard zonation maps. This is further facilitated by the rapid progress in the field of remote sensing, which provides most authentic and accurate information on earth surface features and processes involved. Moreover, information from remotely sensed data can be digitally processed and integrated with other ancillary information using Geographic Information Systems (GIS) that provide efficient tools for collecting, storing, retrieving, transforming, manipulating, and displaying spatially distributed data (Champati ray and Lakhera, 2006). As a result, there has been tremendous progress in the field of geological data integration using GIS and various attempts have been made on spatial prediction of Landslides using statistical models (Westen., 1993; Carrara et al., 1995; Chung et al., 1995, Champati ray, 1996).

2.4.2. Concept of mapping units in landslide hazard studies:

Evaluation of landslide hazard requires the preliminary selection of a suitable mapping unit. The term “mapping unit” refers to a portion of the land surface which contains a set of ground conditions which differ from the adjacent units across definable boundaries (Hansen, 1984). Hazard values are determined on the basis of the principle that future landslides are more likely to occur under those conditions which led to past instability, landslide susceptibility is defined by computing the landslide density in correspondence with different combinations of instability factors (Clerici et al., 1999).

Several methods are proposed to derive the ideal mapping units for landslide hazard zonation. These include grid-cells; terrain units; unique-condition units; slope-units; and topographic units. Grid cell are the division of territory into regular squares of pre-defined size which become the mapping unit of reference (Westen, 1993, 1994). Each of the grid-cells is assigned a value for each geo-environmental factor taken into consideration.

Terrain units, preferred by geomorphologists, are based on the observation made on the natural environment to classify them into different units depending upon its frequent geological and geomorphological change observed during field study or image interpretation.

Subdivision of the territory into Unique Condition Units is particularly straightforward from a conceptual point of view and suited to the use of a GIS where each unit can be considered as homogeneous in the sense of materials, geology, geomorphology and process type, those directly contribute to the instability of slope in different proportions. The size of these units depends on the mapping scale, since homogenous units at a scale of 1:25,000 can often be subdivided into smaller units at a larger scale (Bonham-Carter, 1994; Chung et al., 1995; Westen et all, 2000).

Slope-units are automatically derived from high-quality DTMs, partitioning the territory into hydrological regions between drainage and divide lines (Carrara et al., 1991). Slope units may further be subdivide in to topographic units those are generally the intersections of the flow tubes at a right angel to the contour lines.

The choice of the mapping units is basically purpose specific. In other words the scale of the study, resolution, objective, type and size of the landslides that is to be investigated, and finally the capability of data handling tools influence the selection procedures of mapping units.

2.4.3. Temporal probability

Temporal hazard in a simple sense is the probability of occurrence of any number of landslides events in a particular time step. For example, it can be expressed as the probability of occurrence of one or more landslide events in one year or several years time interval. The definition of any hazard include the parameter like location corresponding to question “where”; time related to “when” finally the size pertaining to “how”. A complete hazard study requires answering of those three questions. Therefore temporal probability determination for landslide hazard became a crucial task from the actual hazard assessment point of view.

Similar to spatial hazard determination the temporal hazard rate can be derived in several methods. But the existing methods are generally based on statistical approaches and extremely data driven in nature. Any of these procedures either calculation of temporal probability from multi-temporal images and aerial orthophotographs or from historic landslide record, both involves a huge amount of data to be handled for the assessment. Guzzetti et al (2005) derived the temporal probability values of landslides at a basin scale using statistical probability distribution model with the availability of multi-temporal landslide inventories.

Various probability distribution models are used to determine the temporal hazard rate of different hazard types. The Poisson probability model is adapted to derive the temporal occurrence rate of volcanic eruptions (Klein., 1882); for landslides (Crovelli., 2001).the binomial probability model was used to derive the temporal probability of landslides (Coe et al., 2000) and debris flows (Keaton et al., 2000).

2.4.4. Hazard quantification:

By the definition of landslide hazard it involves the calculation of a joint probability of a mapping unit that can be affected by landslides with a given time and a given local environmental setting (Guzzetti, 2005). Assuming independence among both the spatial and temporal probabilities a multiplication of the probability factor gives the value of landslide hazard (Guzetti, 2005, Westen, 2006).

Hazard contains the two major components like time (temporal) and space (spatial), along with the additional characteristics like magnitude and frequency. Unlike other natural hazards, estimation of magnitude of landslide hazard is quiet a difficult process as there is no exact method to measure the magnitude, as for instance for earthquakes, where magnitude is clearly defined. For landslide the magnitude term can be correlated either with the amount of volume of material displaced or the area affected (Malamud et al., 2004). The probability of the landslide size, in terms of the probability that a landslide will have an area greater or equal than a given size, is computed using probability density function, as suggested by Malamud et al., (2004) using truncated inverse gamma function, showed that the inverse-gamma distribution has an exponential rollover for small landslides and inverse power-law decay for medium and large landslides. The double Pareto probability distribution proposed by Stark and Hovius (2001) also has a power-law tail for medium and large landslides, with a rollover for smaller landslides. Therefore, quantifying the hazard will depend upon the determination of spatial probability of hazard (susceptibility), temporal probability, and magnitude-frequency analysis (Guzzetti, 2005).

3. Study Area:

The selection criteria for the study area was based on the following conditions a) availability of landslide occurrence date b) authentic locational information of slides along the route corridor c) and finally a genuine problematic situation that is need to handle with a scientific methodology.

Garhwal Himalaya is well known for its fragile landscape and frequent geological hazards, among which landslides are the regular threats over this region. The selected study area is the road corridor passing through a highly rugged terrain of the upper Bhagirathi river valley in Uttarkashi district of Uttarakhand, suffering from frequent landslides especially during every monsoon season. Temporal hazard rate determination becomes more meaningful for this area when an authentic source of historic records on slides exists as the road under study is maintained by the Boarder Roads Organization itself which has been keeping a continuous watch on landslide situation of the road over years.

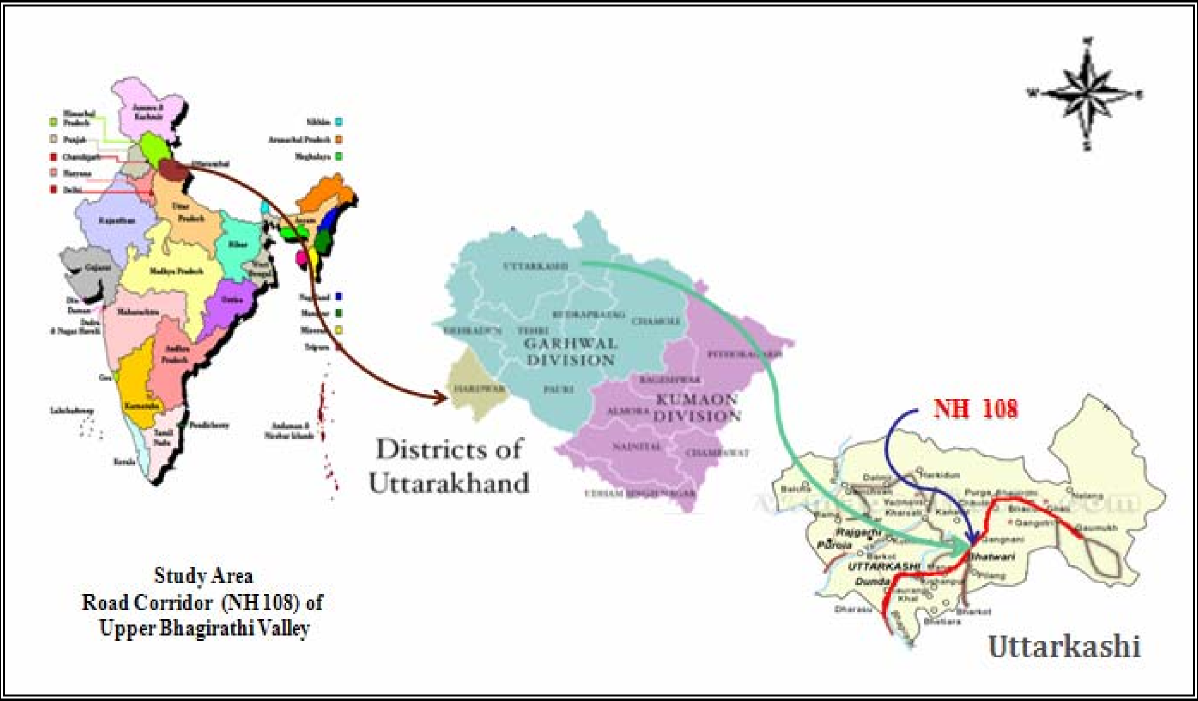


Figure 3.1: Location map of study area

3.1. Uttarakhand, a General Description:

The state Uttarakhand derives its name from Sanskrit for Northern Country or Section as it is indeed among the northern most part and formed as 27th state of Republic of India in the year 2006. In January 2007, the name of the state was officially changed from Uttaranchal, its interim name, to Uttarakhand, according to the wishes of a large section of its people.

Uttarakhand shares it boarder with China (Tibet) in the north and Nepal in the east. The entire state is hilly terrain incorporating the Tethys, Higher, Lesser and Sub Himalayan part along with the great Indo-Gangetic plain falling in the Hardwar and Udham Singh Nagar districts. It covers an area of about 53,500 square km. The state is composed of 13 districts grouped in to two division called Garhwal and Kumaon. Garhwal division includes Chamoli, Dehradun, Hardwar, Pauri Garhwal, Rudraprayag and Tehri and Uttarkashi districts where as Kumaon division includes Almora, Bageshwar Champawat, Nainital, Pithoragarh and Udham Singh Nagar districts.

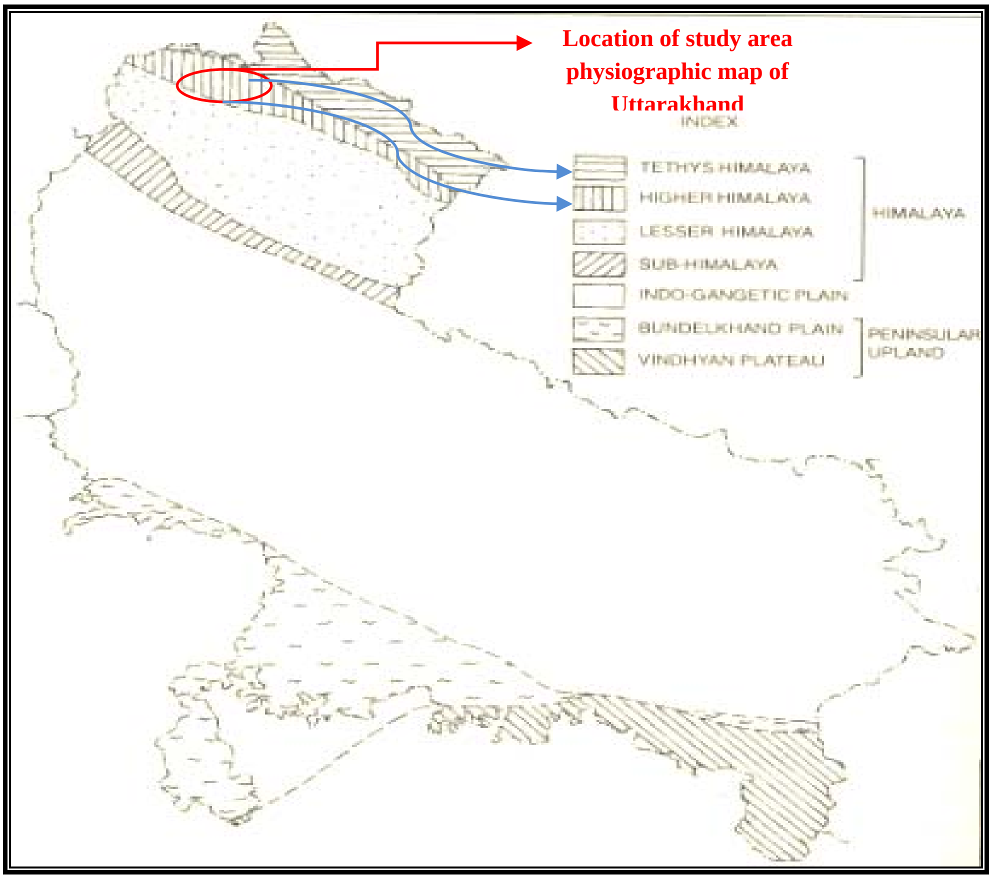


Figure 3.2: Showing physiographic units of Uttaranchal and Uttarpradesh after (Kumar, 2005)

Climatically this region experiences three well marked seasons, summer, winter and rainy seasons respectively. The maximum average temperature ranges between 36°C ± 6°C and the minimum average temperature fluctuates to 5°C ± 2°C according to its subtropical to temperate situations. In summers the maximum temperature i.e. 36 ± 6°C and the minimum temperature is 16 ± 7°C whereas in winters it varies from 23 ± 4°C and 5 ± 2°C respectively. But the higher mountainous parts i.e. the terrain above 5180 meters in Western Himalayas of Uttarakhand lies above snow line and the adjacent lower areas ranging from 1500 meters to 4000 meters remains cool throughout the year and are accompanied by snowfall during winters consequently the temperature drops below 0 degrees .The entire Uttarakhand experiences heavy rain fall specially during monsoons (370-500 mm).

Uttarakhand is a region of outstanding natural beauty. Most of the northern parts of the state are part of Greater Himalaya ranges, covered by high Himalayan peaks and glaciers while the lower foothills are occupied by dense forest. The southern most districts like Hardwar and Udham Singh Nagar fall in

Ido-gangetic plain where the altitudes are less than 1200 meters. An abrupt geomorphic change can be noticed just north to this districts along the Foot Hill fault/Thrust (FHF) where the outer or the Sub-Himalaya begins and the surface gains a height more than 1200 meters. This Zone is primarily composed of Cenozoic Sediments- the Siwalik Super group and is known as Siwalik range. The Main Boundary thrust (MBT) demarks the northern limits of the siwalik Himalaya and region lying in between is referred to as the Siwalik and host synclinal intermontane basin- the Duns .the Dehradun Valley is one of the largest duns found in Dehradun district of Uttarakhand.

The broad zone lying between the Outer Himalaya and Greater Himalaya in the north in Uttarakhand form the third geomorphic zone called the Lesser Himalaya which is mainly composed of Paleoproterozoic sequence. At the south along the Sub-Himalayan zone a narrow belt of Mesoproterozoic and Early Cambrian succession exists. The altitude varies between 1200 to 3000 meters with in the region. The Main Central Thrust forms the northern limit if this geomorphic unit. The Greater Himalaya starts from the north of MCT (Main Central Thrust) and the surface start gaining a mean relief variation between 4800m to 6000m. The major parts of this physiographic unit are having an altitude of more than 3000m. The chief rock formation belongs to the Archaean-Palaeoproterozoic age which constitutes the Central crystalline and Dar formations. The Dar-martoli fault demarcates the northern limit of the Greater Himalaya. This zone is characterized by extremely rugged topography and snow bound peaks like Kamet (7756m), Gangotri (6614m), Chaukhamba (7138 m.), Kedarnath (6940 m), Nandadevi (7817m).the unit hosts a number of glaciers like Gangotri of Bhagirathi River basin, the Pindari Milam, Kaphini and Sunkalpa of Kumaun region.

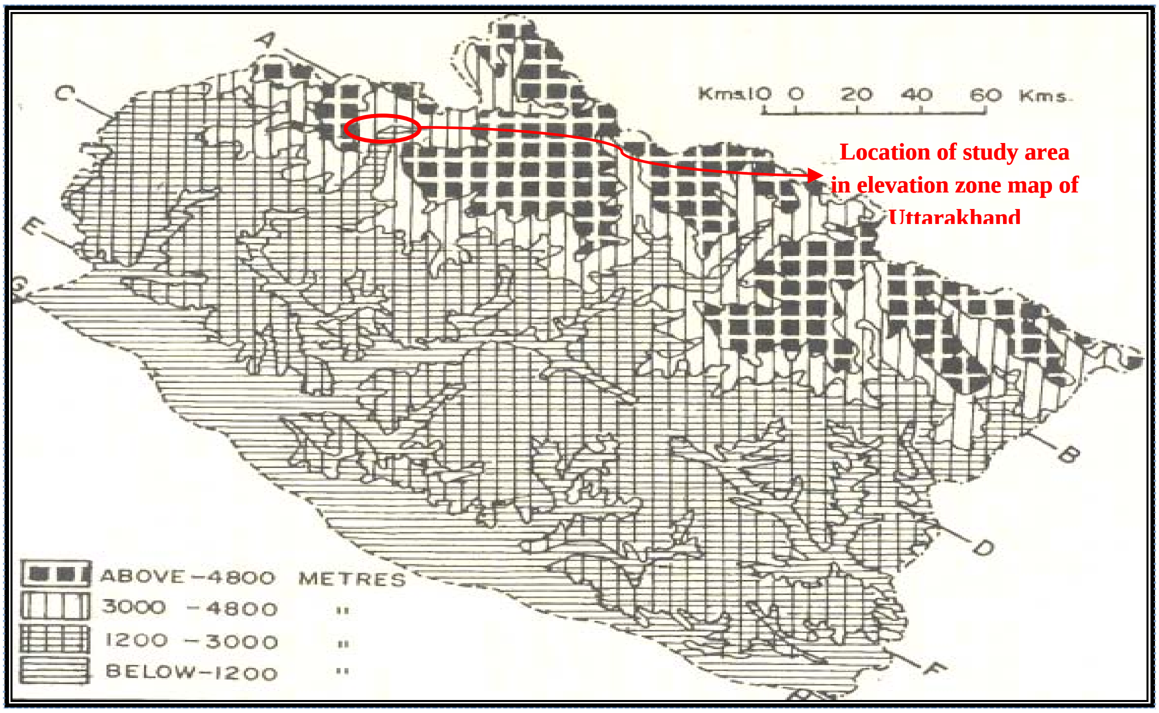


Figure 3.3: Showing the location of study area in the altitude zone map of Uttarakhand. After (Singh, 1971)

The rivers draining the Uttarakhand belong to the Ganges river system where the Ganga, The Yamuna, and Kali are the main glacial fed rivers of Uttarakhand originating at the Greater Himalayan parts of this region. Dendritic drainage pattern is predominant in the higher altitudes and flowing in southerly direction except the areas where flow direction is controlled by structure. This huge amount of environmental variety as well as complexity catch the attention of the earth scientist to understand various natural process and provides an inspiration to work in the field of modelling of those ongoing environmental activities.

3.2. The Road Corridor (NH 108):

The study area is situated between latitudes of 30^0 49’ 00”N to 30 55’ 30”N and longitudes of 78 37’ 00”E to 78 41’00”E along the Bhagirathi river catchment in Garhwal Himalayas. The area is transacted by a national highway corridor connecting Uttarkashi and Gangotri passing through Bhatwari in Uttaranchal State, India. A fifteen kilometres long road stretch between Bhatwari to Gangnani on National Highway 108 is finally selected for the study as the landslides touching the Highway is taken in to account for the temporal hazard assessment. The area falls under survey of India toposheet no 53 J/9. Landslides here are the outcome of complex geological settings, varied geomorphic expressions as steep slopes accompanied by high rate of weathering in association of climatic and other geo-environmental agents. This gets triggered when human activities come in to the picture and natural state is disrupted due to anthropogenic activities. Slope failures are observed frequently during rainstorm and very often with cataclysmic consequences.

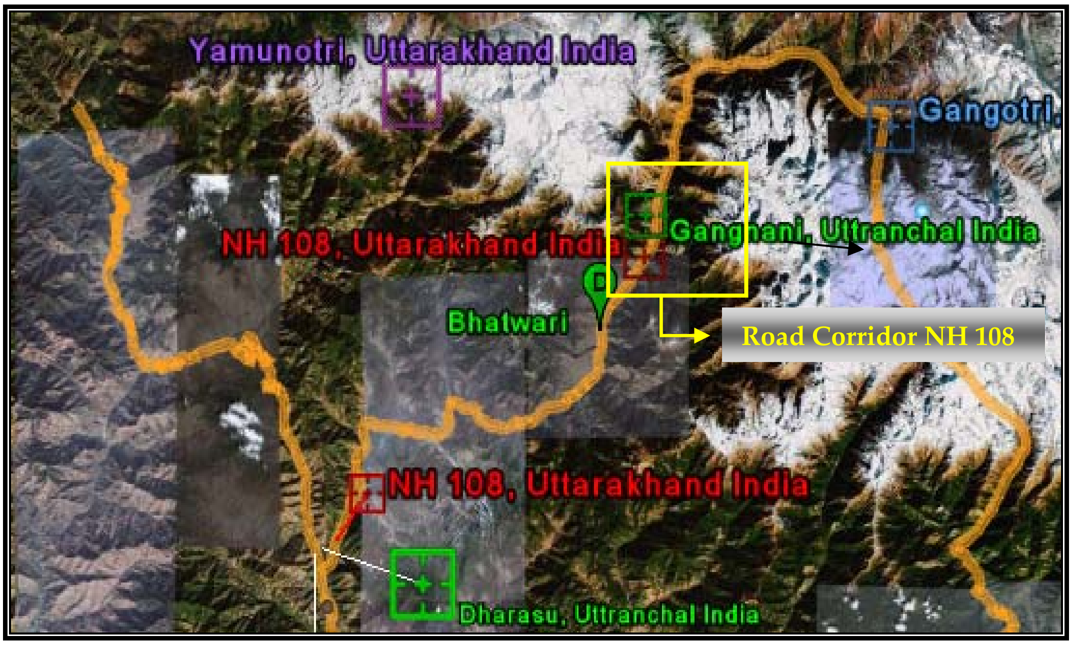


Figure 3.4: Showing the location of the Road corridor NH 108 on Google image.

3.2.1. Geomorphology:

The major landforms observed in the study area are structural, glacial, fluvial, and denudational in origin. Inversion of relief in highly metamorphosed rocks of the study area reflects the impact of active weathering process prevailing over the area. The general geomorphic features include the cliffs, rocky slopes, waterfalls, major and minor ridges and quaternary deposits along the hill slope and the river valleys. The effect of high relief and structural control is well reflected by deep gorges and wide valleys carved by numerous channels. The narrow and confined nature of these valleys towards the downstream in a cross section indicates the continued vertical uplift of the area. Other than the fluvial terraces, the loose Quaternary deposits generated through old rock falls, landslides, glacial, periglacial and hill slope scree processes generally cover the middle valley slopes. The thickness of these deposits varies from 2 m to more than 15 m depending upon the slope amount, aspect and bedding plane of parent rock. The major geomorphic units observed in the study area are highly dissected denudational hills, moderately and low dissected durational hills, river terraces, and various fluvial geomorphic features like point bar, meandering scars, natural levees etc are observed along the entire river course.

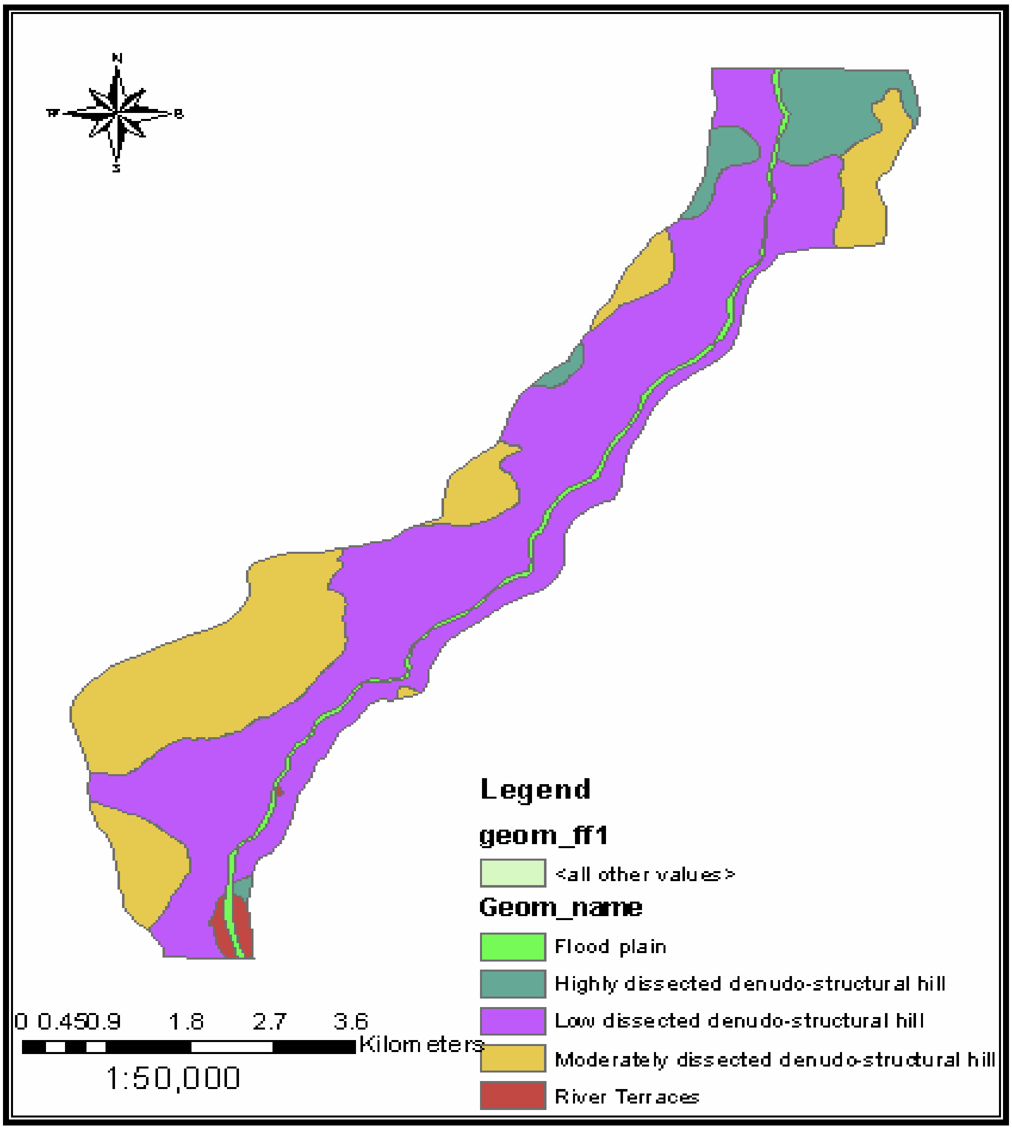


Figure 3.5: Showing the basic geomorphological unit of the study area.

3.2.2. Geology:

In the Uttarkashi District of Garhwal Himalaya four stratigraphic units have been recognized: the Central Crystallines, Martoli Formation, Dudatoli Group and the Garhwal group. Each of these units is separated by major faults. The North Almora 'Thrust' and the Main Central 'Thrust' separated the Garhwal group from the Dudatoli Group in the southwest and the Central Crystallines in the northeast, respectively. The Dar-Martoli Fault marks the boundary between central crystalline of Bhatwari area and the Martoli formation of the Harsil area in the North (Agrwal and Kumar, 1973). The road corridor between Bhatwari to Gangnani falls in central Crystallines. The investigation area falls in the Higher Himalayan region of Uttarkashi and is situated to the north of the Main Central Thrust (MCT) which passes through Sainj Near to Bhatwari. The two group of rocks is separated by Main Central thrust which runs in NW-SE direction and crosses river Bhagirathi near Sainj (20 km from Uttarkashi along NH 108) quartzite, phyllite, Schistose quartzite and epidiorite from the Lesser Himalayan part, while the Central crystalline of gneisses, schist, amphibolites and migmatites. **Central Crystalline Formation:** On the basis of metamorphic grades the rocks of central crystalline are divided into three

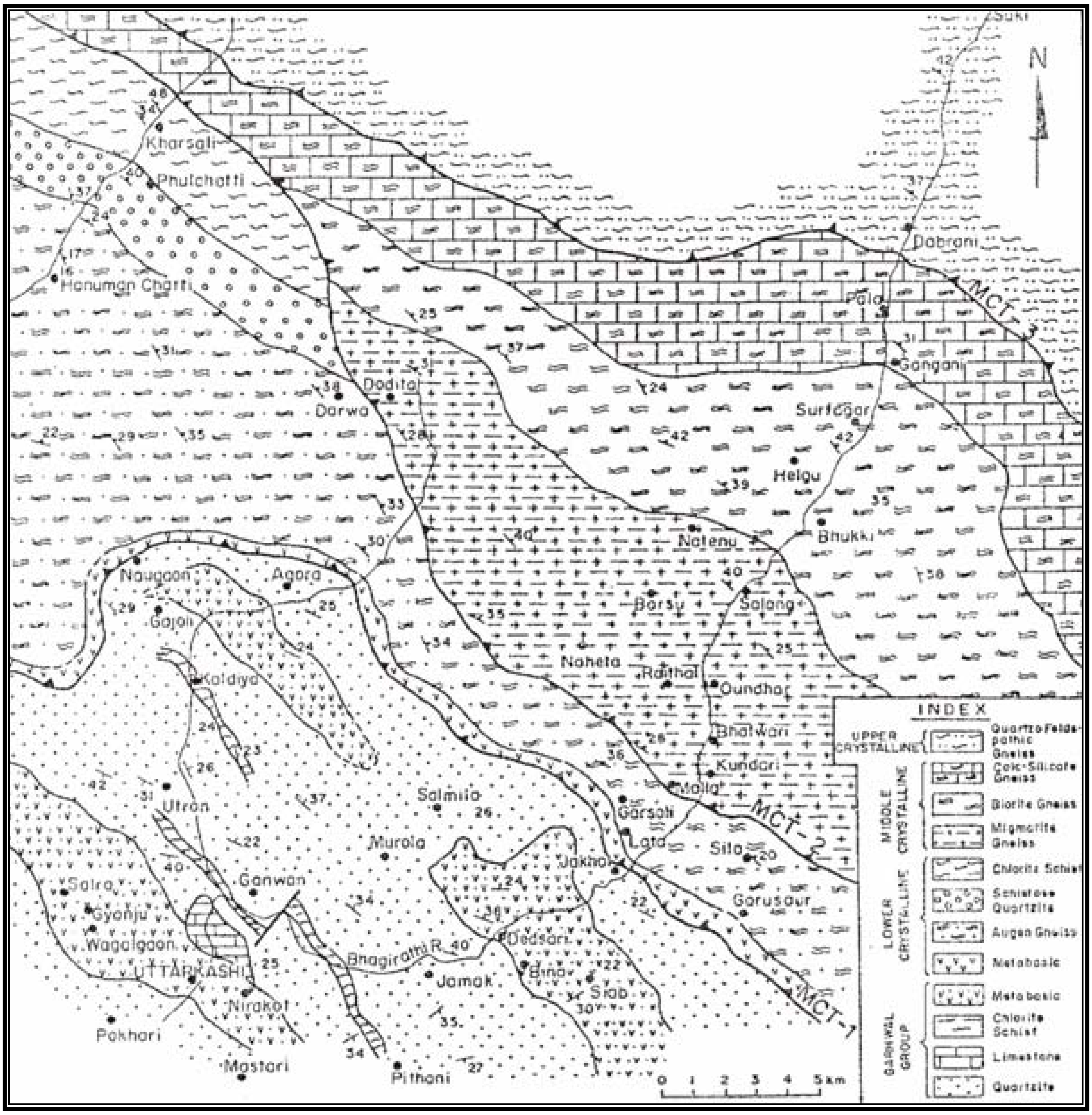


Figure 3.6: Geology map of upper Bhagirathi and Yamuna valleys after (Purohit et al., 1990)

parts viz. Lower, Middle and Upper (Purohit et al., 1990). **Lower Crystallines:** This constitutes low grade metamorphic rock such as chlorite schist, schistose quartzite, biotite schist and mylonitic migmatites separated from Garhwal group by the Main Central Thrust; **Middle crystalline:** sandwiched between lower upper crystallines, are varying types of migmatites such as gneissic and banded migmatites and biotite gneisses etc; **Upper Crystallines:** These rocks are represented by medium to high grade of metamorphism as evidence by the presence of kyanite-schist, garnetiferous-mica-schist and biotite-gneisses. The litho-stratigraphy of the Central Crystallines can be summarized as follows.

Place Name	*Bhagirathi Valley*
Formation at northern boundary	Martoli Formation
Fault at southern boundary	Dar-Martoli Fault
Specific Rock Types of study area	Banded Augen gneiss
	Kyanite-Garnet-Mica-Schist and interbedded-Augen and Porphirytic gneiss
	Banded augen gneiss and Garnet-mica schist containing tourmaline.
	Migmatite zone of Mica-schist, gneiss, granite, marble, calc-silicate with amphibolite.
Fault at southern boundary	Main Central Thrust
Formation at southern boundary	Garhwal group

Figure 3.7 : Showing the lithostratigraphic units of the study area after (Agrwal and Kumar, 1973)

3.2.3. Drainage:

The study area is drained by one of the holiest stream of India the Ganges also known as Bhagirathi at the upper reaches. It originates at Gangotri Glacier in Gaumukh in Tethys Himalaya forming a broad U-shaped valley near Jhala at it upper course. Afterward it continues to cut 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 sides. The dendritic drainage pattern is predominant over the area. And also sub-parallel to parallel pattern is observed along the hill slopes. The entire road corridor of NH 108 is running parallel to river Bhagirathi.

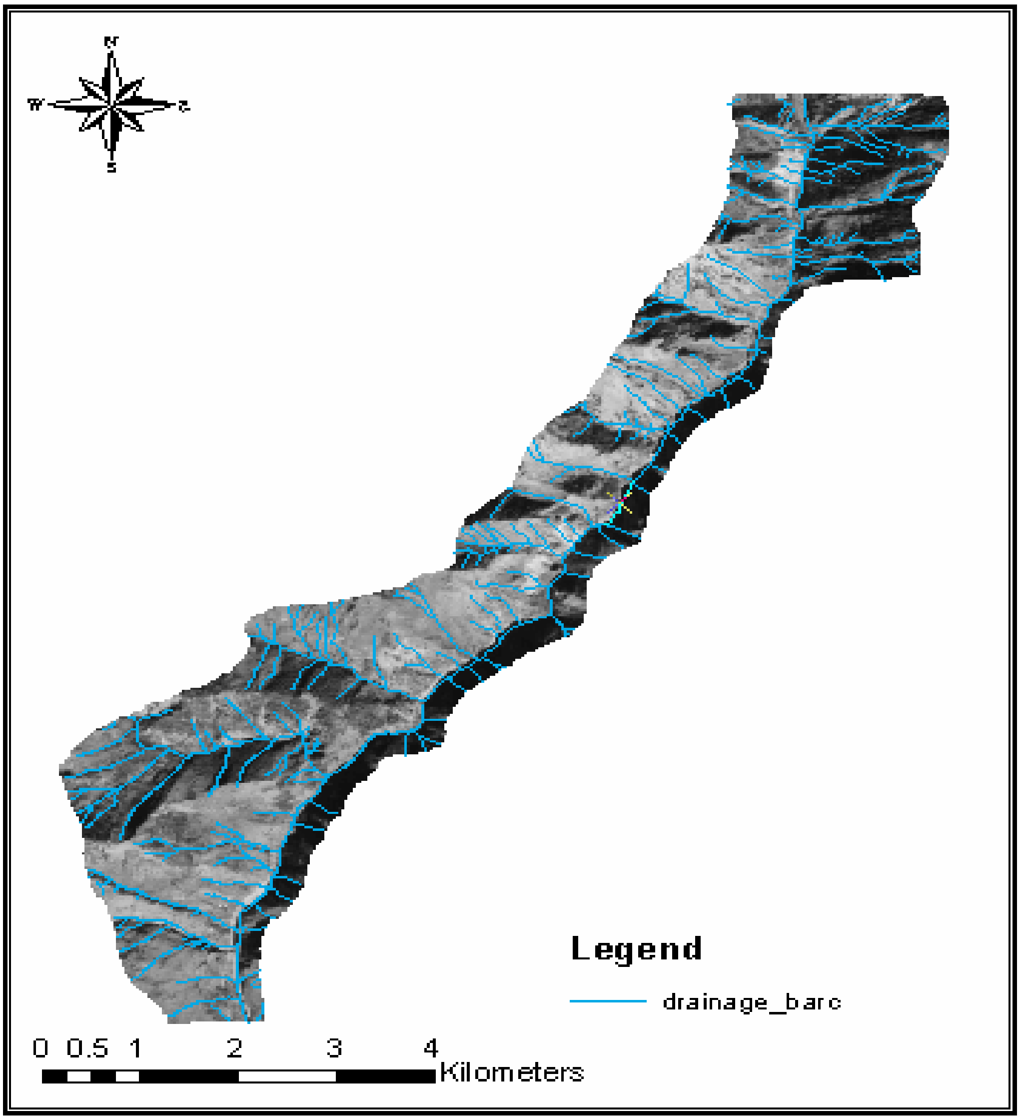
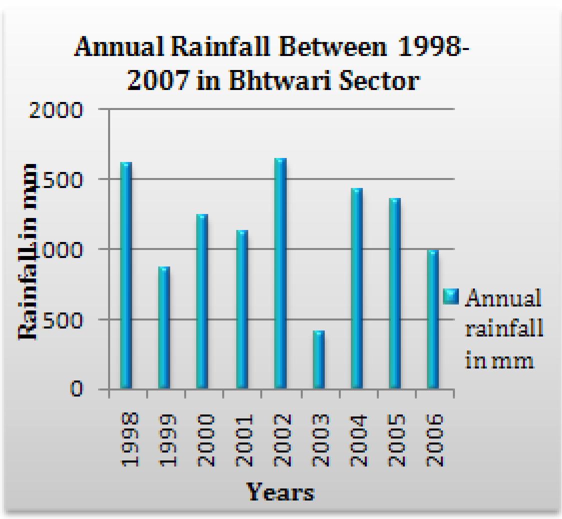


Figure 3.8: Showing the drainage main river Bhagirathi and its tributaries of the study area

3.2.4. Weather and climate:

The road corridor experiences a subtropical temperate climate throughout the year because of high altitudinal location. The maximum elevation observed in the area is 3543m and the minimum elevation is 1159m, with respect to the mean sea level. The temperature varies between 18 degrees to 25 degrees in summer. It receives a heavy rainfall during monsoons. On average there are 100 rainy days in a year and average annual rainfall in the area is around 1200 mm. around 50 % of the total rain fall is received during the months of July August and September. the average monthly rain fall is over the road corridor is found to be 1200 mm as the daily rainfall observations of Bhatwari sector is collected from the Uttarkashi collectorate office.



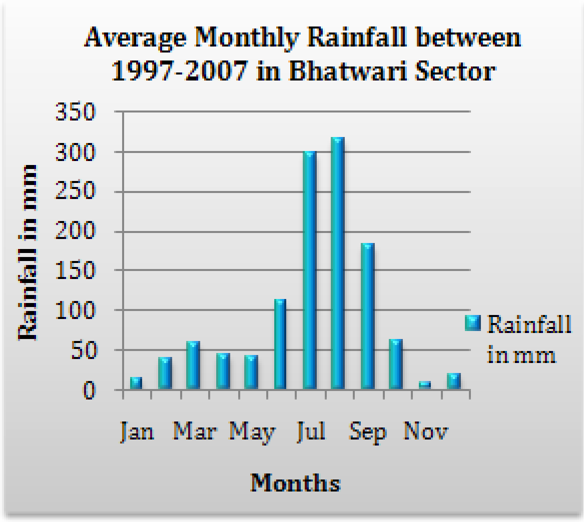


Figure 3.9: Showing the average monthly and annual rainfall of the Bhatwari sector (Rainfall register, Collectoate rate office Uttarkashi)

3.2.5. Soil:

Wide range of variation in soil type can be observed in the entire road corridor. The 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 practiced in abundance. Depending upon it altitudes and geomorphic situation the change in soil characteristic is noticeable in the area. Very steep slopes are mostly left without any soil cover.

3.2.6. Natural Vegetations:

The high altitudinal zones of are characterized with beautiful pasture lands which contains grasses with plants, like Piceasp, Pinus, Cesrus Deodar, Karsu, Quereus semecarpifolia, Rhohododendrron, Camapanualatum, Betulautilus etc. the moderate to lower altitudinal slopes are generally used in step cultivation for growing potatoes ,pulses and green leaves. The natural vegetation predominant over these slopes is Shores Robusta, Dalbegia sisoo and Pinus sp.

3.3. Landslides of the Study Area

The road corridor NH 108 is vastly occupied with various big and small landslides. A separate landslide inventory was maintained for the entire study area. These landslides of this region are generally anthropogenic by origin. Construction of roads along the steep hill slopes is the primary cause of behind the instability of the slope. In a road stretch of 15 km length has experienced 81 landslip events of recognizable dimension in past 25 years. Various slides present in different state of activity and several sort of material involve in sliding has been identified during the field study.

The first slide in the study area is observed at kilometer 56.3 at Bhatwari. The toe cutting caused the entire 40 meters road stretch subsided in to Bhagirathi. The same place suffered subsidence two times in year 2007 and still in active state. Generally debris of small rock fragments and loose material was involved in sliding. This is rather a fresh slide occurred in the area. There is continuous zone of old landslides which involves both rock and debris slides has been found between kilometers 57 to 58.

Location-56.3 km on NH 108
State-Active
Type- Debris slide (Subsidence due to toe cutting)

Location- 57- 58 km on NH 108
Old Slide zone extending over 1 km
Bright signature due to on going road widening.

Location- 60.9 km on NH 108
State-Active
Type- Rock Slide

Location- 57.2 km on NH 108
State-Old
Type- Debris slide (transforms into Debris flow during rainstorm)

Figure 3.10: showing examples of the landslides in the study area

Ongoing road widening has caused the reactivation on these slides along with initiation of new slides on this man modified slopes. A natural slide located near Thrang Nala is a natural debris flow still in an active sate has been observed during field. Slide near Helgu village at kilometer 65.4 is a typical example of planner rock failure and first occurred in 1994. This slide is found still in active sate. Most of the vehicles for Gangotri Pilgrimage get blocked on the way due to frequent recurrence of this slide at this location.

An old slide zone extended over a kilometer along the road between kilometers 67 to 68 on NH 108. All the slides have their crown at 100-150 meters above the road. One of them located at kilometer 67.8 has a recurrence of 27 times in last 25 years.

Figure 3.11: Showing the various types of slides found in the study area

Another important slide location is near Gangnani Bridge at kilometre 68.300 famous as Gangnani slide which occurred along the road with a crown around 50 meters above the road extending unto the river with volume more than 4000 cubic meters in year 2007 during field survey.

Slope failures along the road corridor of NH 108 involves a variety of movement of weathered rock/debri like falls, planner failures along rock joints, slides, flows etc. The dominating failure types observed in the entire study area are debris slides, followed by Rock slides. Few of debris slides have turn into flows during high intensity rainfall. Shallow, translational slides are found in abundance along the the corridor. While most of the slide occurred in the slopes greater than 35 degrees in exposed bed rocks and on overlying loose material with vegetation cover.

4. Concepts and methodology of the research

The chapter discusses the methodology followed to achieve various objectives of the research. It also describes the specific statistical concept used to quantify the landslides hazard scenarios.

4.1. Temporal landslide inventory generation

The literature review carried out for this research reveals the fact that there is no single ideal method for constructing a landslide geospatial database .Therefore a combination of several efforts are made to generate the inventory which includes both the collection of historic records along with the use of remote sensing tool for accurate mapping of landslides. Finally the GIS tool is exhaustibly used to correlate the temporal information associated with each slide and adding several other attributes related the dimension, type, state of activity of the slides .Therefore it can be said the literature review proved to be extremely helpful as it provide the basic path of construction of temporal inventory of landslides .The steps followed to generate the inventory has been discussed in detail in chapter 5.

4.2. Deriviation of homogeneous road sections:

This research specifically aims at deriving the spatial and temporal hazard rate of the road corridor under study. Therefore the determination of mapping units on the road corridor was of primary importance. Here also the concepts of slope unit and (Carrara et al., 1991) and Unique condition Unit (Westen et all, 2000) method was adapted as the slope and lithology factor was considered to obtain the homogeneous road sections for which the temporal and spatial probability of landslide hazard was calculated. The methodology consequently includes preparation of slope and lithology layers for the road corridor that has been primarily taken from Indian institute of Remote Sensing (IIRS), which is a premier institute in the field of remote sensing based landslide studies. A landmark in this respect can be the Landslide Hazard Zonation (LHZ) atlas that was prepared in the year 2001 for Uttaranchal and Himachal Himalayas using 14 different terrain parameters. However, the road stretch was divided into different sections according to it slope and lithology conditions and considered as mapping units for the present research.

4.3. Temporal probability of road sections:

Landslides are found to be among the complex natural hazards. A lot of uncertainty is associated with this phenomenon to occur in nature. Man is putting a continuous effort for quantifying this uncertainty of hazard for future preparedness and mitigation purposes. This quantification of uncertainty involves the incorporation of mathematical and statistical models into natural sciences. Such a statistical model is Poisson probability model. Crovelli (2000) has provided a straightforward description of the natural process and the probability models quantifying them. The idea can be summarised as follows

4.3.1. Important philosophical ideas about probability models (Crovelli, 2000):

- Probability is a numerical measure of uncertainty regarding nature.
- A probability model is a mathematical model that incorporates our uncertainty.
- Probability models are an approach to deal with the limitations to our knowledge of natural processes.
- Probability models are used for purposes of description and prediction of physical processes in nature.
- Randomness is an assumption of probability models, not natural processes. Hazards do not occur at random in nature, but they do occur at random in the models.
- Natural processes do not follow a particular probability distribution. We will always be uncertain of nature because of our limitations in understanding.

Hazard processes are deterministic as there exist a cause and effect relationship, but because of our limitations of complete information about hazards, we resort to probability models that incorporate our uncertainty.

4.3.2. 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 number of landslide events that occur in disjoint time intervals are independent.
- The probability of an event occurring in a very short time is proportional to the length of the time interval.
- The probability of more than one event in a short time interval is negligible.
- The probability distribution of the number of events is the same for all time intervals of fixed length.
- The mean recurrence of events will remain the same in the future as it was observed in the past.

The probability of occurring n number of slides in a time t is given by

$$P= [N (t) =N] =\exp (-\lambda t)*[(\lambda t)^{n} /n!] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (1)$$

n=0, 1, 2, 3…….

Where

N: is the 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.

Definition of recurrence intervals {Ti, i = 1, 2, …, n}:

T1: Time until the first landslide

Ti: Time between the (i – 1) st and the i th landslide for i > 1
n landslides will have n recurrence intervals.
Theorem – Recurrence intervals {Ti, i = 1, 2, …, n} are independent identically distributed exponential random variables having mean recurrence interval (μ) equal to the reciprocal of the rate of occurrence, i.e., $\mu = 1/\lambda$.

For landslides, the mean recurrence interval (μ) is the average time interval between landslides.
$\lambda = 1/\mu$
Therefore

Probability of occurrence no landslides will be

P [(N) t=0] = exp (-λt) ………………….. From eqn no (1)   n=0

Probability of not occurring no landslides i.e. the probability of occurring any number of slides (one or more)

$P [N (t) \geq 1] = 1- \exp (-\lambda t)$
If t is fixed and $\mu \to \infty$, then $P\{N(t) \geq 1\} \to 0$.
If μ is fixed and $t \to \infty$, then $P\{N(t) \geq 1\} \to 1$

Example

Suppose the 3 landslides occurred in a fixed time (25 years).
N=3
t=25
Therefore λ (average rate)= 0.12

For a 25 year scenario

$P [N (t) \geq 1] = 1- \exp (-0.12*25)$
$= 1- 0.05$
$= 0.95$

For 5 year scenario

$P [N (t) \geq 1] = 1- \exp (-0.12*5)$
$= 1- 0.55$
$= 0.45$

4.4. Spatial susceptibility:

Spatial susceptibility of the road corridor was derived using another probabilistic statistical approach called information value method (Yin and Yan, 1988). The probabilities of landslide occurrence are derived in terms of information values i.e. from the land slide density of past slides occurred in each unit area and the entire area.

.

$$IA_{j\rightarrow T} = \log \frac{Si / Ni}{S / N}$$

Where,

$IA_{j\rightarrow T}$ = Information provided by feature A and state j for
Event T to happen offered
N = Total number of grids in the study area
Ni = Number of grids having variable I
S = Total number of grids having slides in the whole area
Si = Number of slide grids occurring within the `I' variable grids
From our probability consideration this is equivalent to:

$$IA_{j\rightarrow T} = \log \frac{P\{T \mid A\}}{P(T)}$$

Where, $P\{T \mid A\}$ is the conditional probability and P (T) is the prior probability of event T to happen.

5. Database Preparation:

This chapter mainly deals with two phases called collection of historic data on landslides and corresponding digital database generation. It illustrates the methodology followed for collection of historic landslide records from government organization and standardization of the available data into required format for digital landslide inventory preparation. The standardized database is further used for the derivation of temporal probability landslides along the route corridor. The chapter describes the proposed form of data extraction into tabular format. It includes the preprocessing of satellite data and database generations for extracting homogeneous road units on the route corridor under study i.e. National Highway 108.

5.1. Data Collection:

Data collection phase involves the preparation of tabular data format which meets the need for digital landslide inventory generation and temporal probability calculation. It also involves the decision making process regarding the institutional survey which will be more reliable for providing temporal information on landslides occurrence.

5.1.1. Institutional Survey:

Institutional survey has been conducted as per the requirement of historic record of landslides on NH 108, the Boarder Roads Organizations is chosen as the primary institution for collection of the same. The Boarder Roads Organizations popularly known as BRO is formed Under the inspired leadership of Late Pandit Jawaharlal Nehru was on 07 May 60, as a road construction executive force, partly integral to and in support of the Army and primarily conceived to meet its strategic requirements.

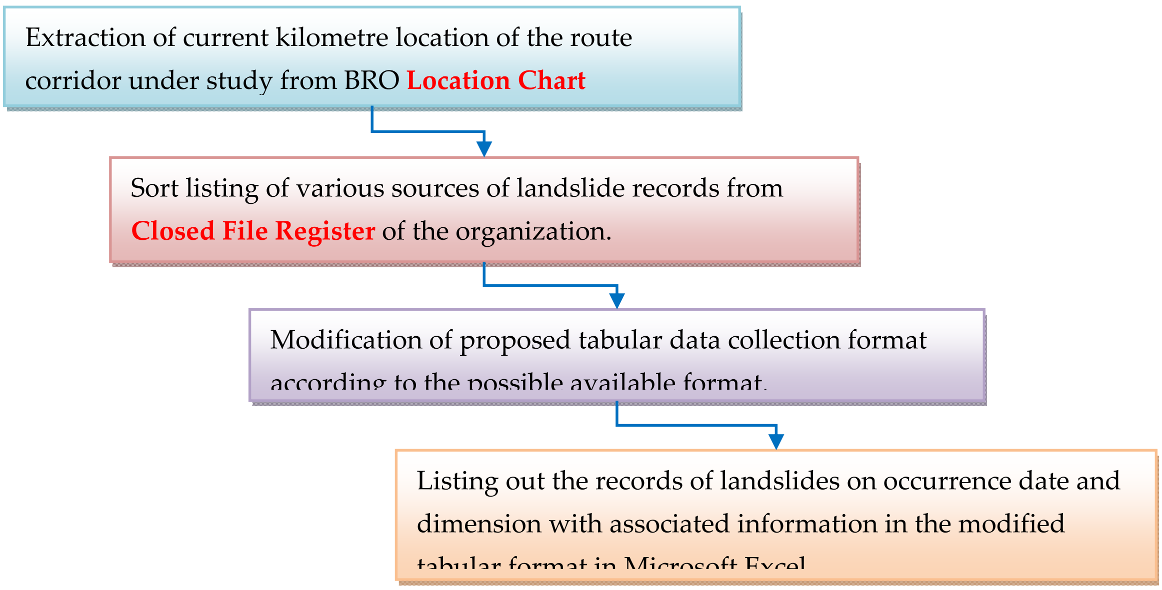


Figure 5.1: Steps followed for collection of historic records of landslides

Headed by a Director General Border Roads (DGBR), as the Executive Head, it provided a General Reserve Engineer Force (GREF), as the execution force, under the Ministry of Surface Transport, to build and maintain roads, through an establishment of Chief Engineer Projects. The GREF was a unique force, conceived as an unarmed, civilian Organization but uniformed, modeled and trained on a military pattern (BRO, 2007). The main task of this organization is development of road network in boarder states chiefly the roads connected to the international borders as well as maintaining the roads and makes them through as soon as possible after any kind of natural or anthropogenic disastrous events.

According to the predefined strategy of obtaining 30 years landslide record on their occurrence date, 21 working days are allotted for the whole work. At the beginning the nearby BRO office situated at Rishikesh has been visited and information on the roads of Uttarakhand has been collected. Finally the main BRO office at Tekla Uttarkashi i.e. 1442 BCC (Bridge Construction Company) has been visited.

File Name	*Type of Records*	*Records Details*	*Data Quality*
HLS (History of Landslides)	Quarterly Report on significant landslides	Occurrence date, Kilometre location, size ,volume of material removed from road for each slide	Regular, but the major landslides at significant slide places are reported. **Quality: good and complete.**
RLS (Register of Landslides)	Decadal report on each small landslide hitting the road	Occurrence date, Kilometer location, size, volume of material removed from road for each slide	Irregular and incomplete records. **Quality: Not good and incomplete.**
DRS Files (daily Road Stirrup)	Daily road situation report with proper statement of reason of Blockages.	Occurrence date, Kilometre location, size, volume of material removed from road for each slide	Extremely regular reports on reasons of road blockage consequently short disruption due to very small slides on roads are also reported on a daily basis. **Quality: Very good and complete.**

Table 5.1: Source of historic records on landslides in Boarder Roads Organization

First and foremost the kilometer location of the NH 108 between Bhatwari to Gangnani has been confirmed from route chart available in the organization. Then the closed file Register has been checked for past files available within the office record room. This revealed the most useful information regarding the landslide records that other than the Landslide Registers there are two more source of landslide information exist which are rather reliable and complete. Mainly three types of record are checked a) RLS files (Register of landslides) b) HLS files (History of landslides) c) DRS Files (Daily Road Stirrup).

The daily Road Stirrup files are found since 1988 December and have been checked for each day up to 2007 for causes of road blockage on NH 108 among which the landslides are found to be the principal reason for the same. Thus DRS files proved to be the most reliable source of slide records. HLS files are found from 1982 onwards so that almost all slide records are available in desired format and DRS reports are cross verified with respect to HLS records.

Figure 5.2: Showing the files checked during institutional survey for extraction of historic records of landslides.

Some missing information was supplemented with the help of RLS file records. Finally slide records since1982 onwards has been collected successfully.

Prior to the institutional survey significant discussions were made to the scientists of IIRS (Indian institute of Remote Sensing, other than the supervisor himself and Wadia Institute of Himalayan Geology, working on landslides especially, regarding the objectives of the present study. Admirable cooperation has been received from the scientists of respective institutes. Last but not the least remarkable amount of cooperation has been offered by the C.O. of BRO and 2nd in Command as well as the E2 section in charge and other employees during the data collection period from the organization itself. That reveals the noticeable difference between an organization under Indian Army and other government departments. The date and size information of landslides on NH 108 are unpublished information that has been extracted into the required format in excel sheet and BRO has given full cooperation in sharing such a use full information contained in their office files for last 25 years. The final design of tabular data format has been given in annexure.

5.1.1.1. Difficulties faced during data collection:

Some difficulties are also being faced during extracting the fruitful information. This is mainly due to change of kilometer location of the same place because of various reasons. The reservoirs of Teheri Dam caused complete submergence of Teheri town and 40 villages and partial submergence of 72 villages by the year (Teheri dam, 2002). This consequently caused submergence of 51.7 kilometers of road length of NH 108 under water. On the other hand renaming of the old road from RUHL to NH 108 and assigning a new location to it created some confusion over the area of interest.

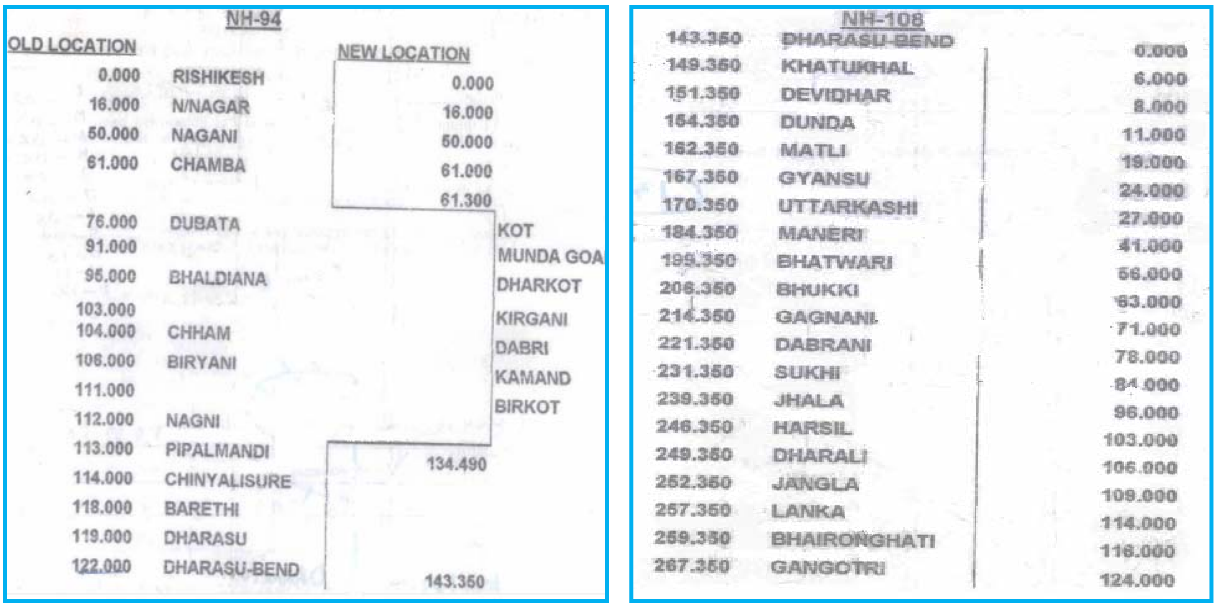


Figure 5.3: Showing the location chart of BRO on NH 108

During 1980s the location Dharasu-bend was situated kilometre 122 on RUHL road. Now the same place is at kilometres 143.350 can be found in BRO Location Chart fig 4.2. This is because of submergence of 51.7 kilometres of road length under water of Teheri Dam Project just after Chamba to Nagni on NH 94. Consequently when the new road was constructed it took an increased length of 21 kilometres and 350 meters. Thus all the location on NH 94 as well as on NH 108 after Chamba is increased by 21 kilometres and 350 meters.

The road stretch under study is (NH) 108. It starts from Dharasu-bend which is situated at 143.350 kilometres on NH 94 from Rishikesh. The road is actually bifurcating from NH 94 at Dharasu-bend towards Gangotri, one of the most popular Hindu pilgrimage destinations of India. Previously the whole road stretch starting from Rishikesh to Gangotri was known as RUHL road i.e. Rishikesh Uttarkashi Harsil Lanka Road. From the year 2002 September this road is renamed as NH 108 From Dharasu-bend onwards and kilometres 143.350 was marked as kilometres 0 on NH 108.

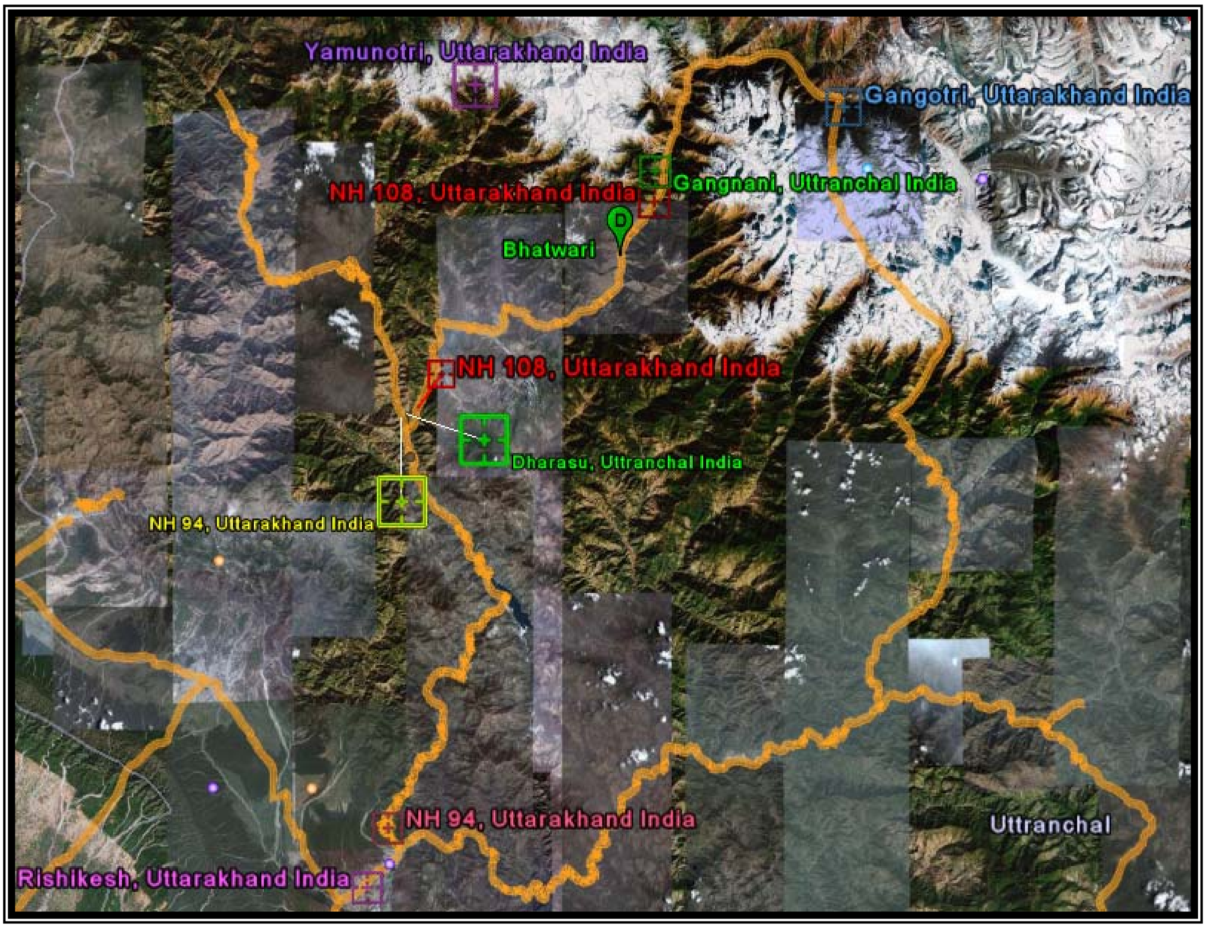


Figure 5.4: Showing entire road map on Google image

5.2. Data Preparation:

Data preparation is done in three steps, a) pre-field satellite data pre-processing b) field survey and c) post-field vector layers generation on landslides and other related geo-environmental factors essential for carrying out the study.

5.2.1. Satellite Data Preparation:

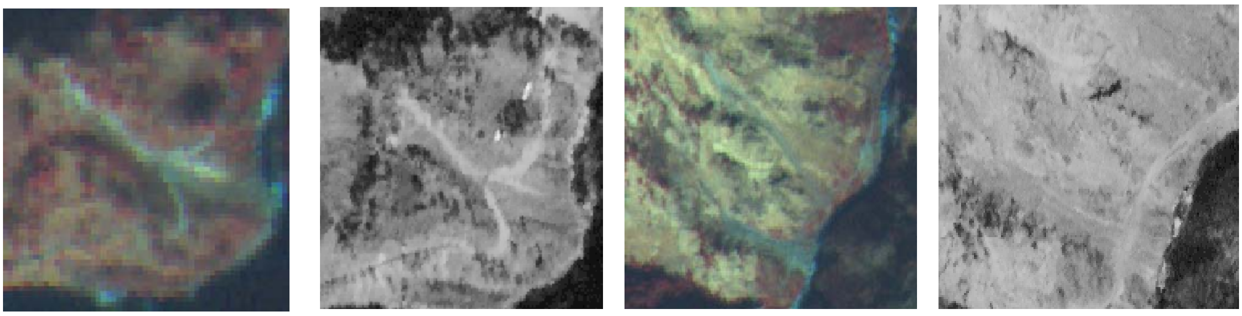
Satellite data was prepared for field identification and mapping of landslides according to BRO data. Other than this the satellite data is also used for spatial database generation for landslides. The digital remote sensing products used for the study are as follows.

Satellite Name	Sensor Type	Acquisition date	Ground Resolution	Projection System
Cartosat 1	PANA	16-JAN-07	2.5 mts	UTM ,WGS 84
IRS P6	L4MX	11-JAN-04	5.8 mts	UTM ,WGS 84

Figure 5.5: Description of the Digital Remote Sensing Products used in the Research

The PAN image of Cartosat-1 is the high resolution image used for landslide mapping in large scale. In addition to that the IRS P6 Liss4 image is also used for improvement of spectral characteristic of the PAN image which in turn helps in better identification of the image features.

Various radiometric enhancement techniques had to be applied before Geometric correction as because the entire image was dominated with very dark signature due to low sun angle during acquisition time and extremely rugged terrain conditions. These contrast enhancement techniques improves the visual image analysis (Jensen, 1996). Due to the non availability of multispectral image of same time period, MX image of an old date has been used and prior to that through visual image interpretation the homogeneity of the area, over acquisition time period of two images used has been verified and very less change has been found through time other than the course change of the river in the some places which are mainly lying out of the area of interest.

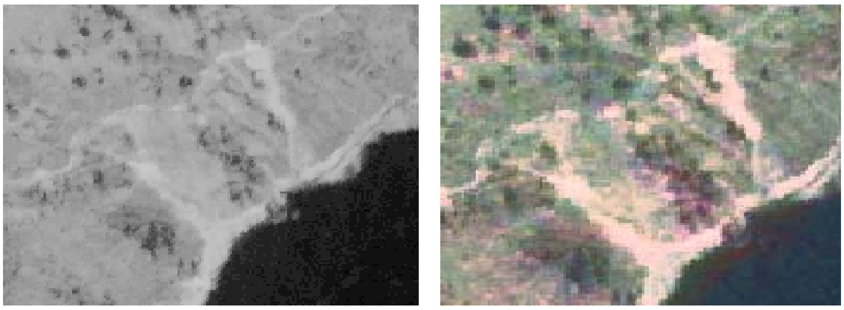


11-JAN-04 16-JAN-07 11-JAN-04 16-JAN-07

Figure 5.6: Showing homogeneity of the study area over acquisition time period of two images

3 separate bands of IRS P6 Liss 4 MX sensor has been ordered from NRSA with special request as complete FCC was not available for the required area. In order to obtain the FCC for the area the band are co-registered with respect to Cartosat1 PANA image and therefore stacked to derive the FCC to improve the Finally the stacked FCC (5.8 m) was fused with PANA (2.5 m) using Modified IHS Resolution Merge Technique in ERDAS Imagine 9.1 software which produced an MX image with higher spatial resolution and additional spectral information. The visual quality of image obtained from Pan-sharpening of Liss 4 image enabled detailed interpretation of landslides and associated environmental features (Nichol and Wrong, 2005).

PANA Image **Merged Image**



PANA Image **Merged Image**

Figure 5.7: Showing the enhanced landslide features on merged image

Anaglyph image was also prepared with the help of Cartosat-1 stereopair and SRTM dem which was insufficient for identification and mapping of small road cut active slides at scale of 1: 10000.

This data has is mainly being used in mapping of landslide in the field as well as during the preparation of digital database on landslides by screen digitization.

5.2.1.1. Ancillary Data

Survey of India toposheet of a scale of 1:50000 were used for reference purpose and in identification of human occupants in the study area.

Sheet No	Scale	Year of survey	Year of publication	Projection system
53J/9	1:50000	1962	1966	polyconic

Table 5.2: Showing the details of toposheet used for the study

5.2.2. Field survey:

The field survey was conducted for the fulfillment of two objectives. The first objective was to identify the landslide location of the slides given by the BRO and corresponding size verification and type recognition and field mapping of slides respectively. And in second objective was to prepare an accurate road layer by GPS tracking.

5.2.2.1. Landslide Identification and Field mapping of slides:

The database prepared in excel sheet and printouts of georeferenced satellite images with an overlay of the road, approximately digitized from the image in the 1:10000 scale of the road corridor under study were taken for the field mapping purpose. These two materials are exhaustibly used during the field survey. Each record of slide present in the database was verified for its kilometer location on the road under study. The measurement of length of slide along the road and locational identification of slides found within one kilometer were done by Meter Wheel provided by the BRO. Therefore the slides identified in the field were approximately mapped on the image. Within 15 kilometer road stretch 81 slides are identified. These events were reported 309 times in last 25 years in the BRO files out of which 279 records can be correlated according to the field verification. Because of ongoing road widening process the signatures of some of the old slides are destroyed consequently cannot be correlated in the field with the database prepared from BRO file information. Finally each of the slides are measured for their length along the road and classified according to their state of activity as well as the material involved in sliding.

5.2.2.2. GPS tracking of the Road:

In order to obtain an accurate road layer of the route corridor under study GPS tracking was done using a GPS Tuner. It is an off-road navigation for pocket PC device. This device is used for capturing points along the road while travelling by a car at a regular interval of one second in tracking mode. A tracking data saves the path as track points along with its geographical coordinate (latitude and longitude) and some additional information like altitude, speed heading information etc. A previously saved track can be converted in to route data. Basically a chain of waypoints defines a route which are points having geographical coordinates like track points.

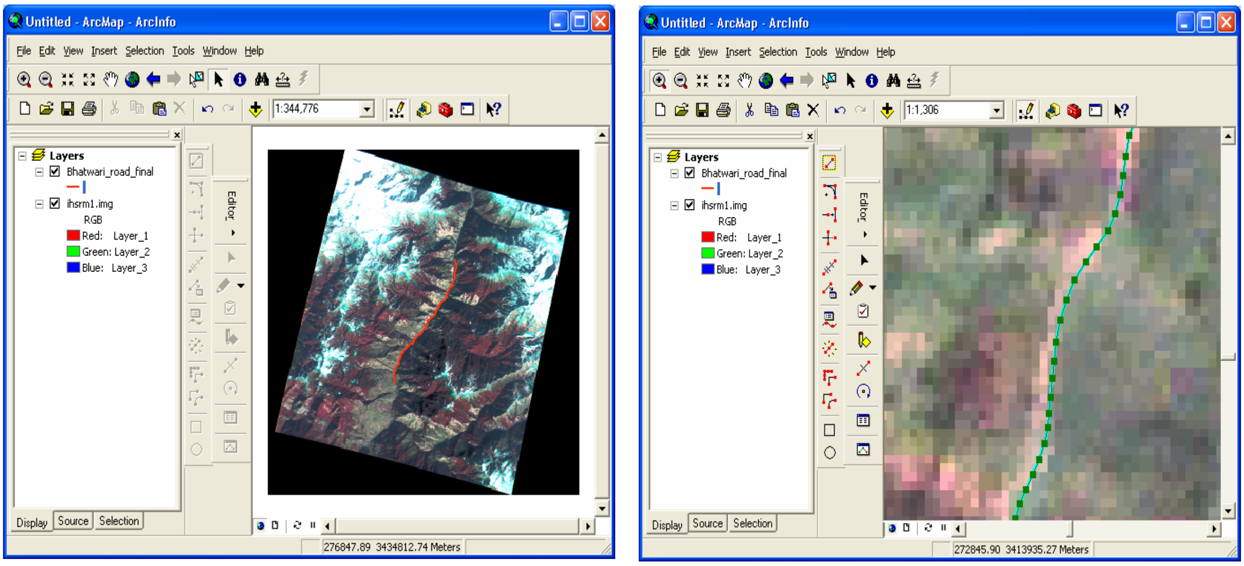


Figure 5.8: Left-road layer generated for the whole study area; Right- point taken in regular interval of one second in waypoint mode during GPS Tracking.

Those points are saved in GPX format in the memory. Software called GPX2shape-0.69 converter is downloaded from the web and therefore converted to ESRI shp format during post field data layer generation session. Thus the road layer was generated with all the turns existing in reality over the road. This is mainly done because to obtain the exact road length with all the existing turns in the road. the associated reason was to get a appropriate road layer in the shadow regions of the image. Finally it helped to locate the landslide according to location given in the BRO files.

5.2.3. Post-field Vector Layers Generation:

The post field vector layers generation for the road corridor is attempted in two steps a) landslide Database creation b) extraction of mapping units based on homogeneous geo-environmental conditions existing along the road corridor. In other words dividing the road corridor into different homogeneous sections which involves derivation of the Unique Conditions units based on terrain characteristics.

5.2.3.1. Landslide database generation:

The digital landslide database generation is performed in two steps. In the beginning the screen digitization of the slides was done on PAN-L4 MX merged image using ARC GIS 9.1 software. During digitization each of the slide are referred to the field conditions based on field mapping of slides in printed image.

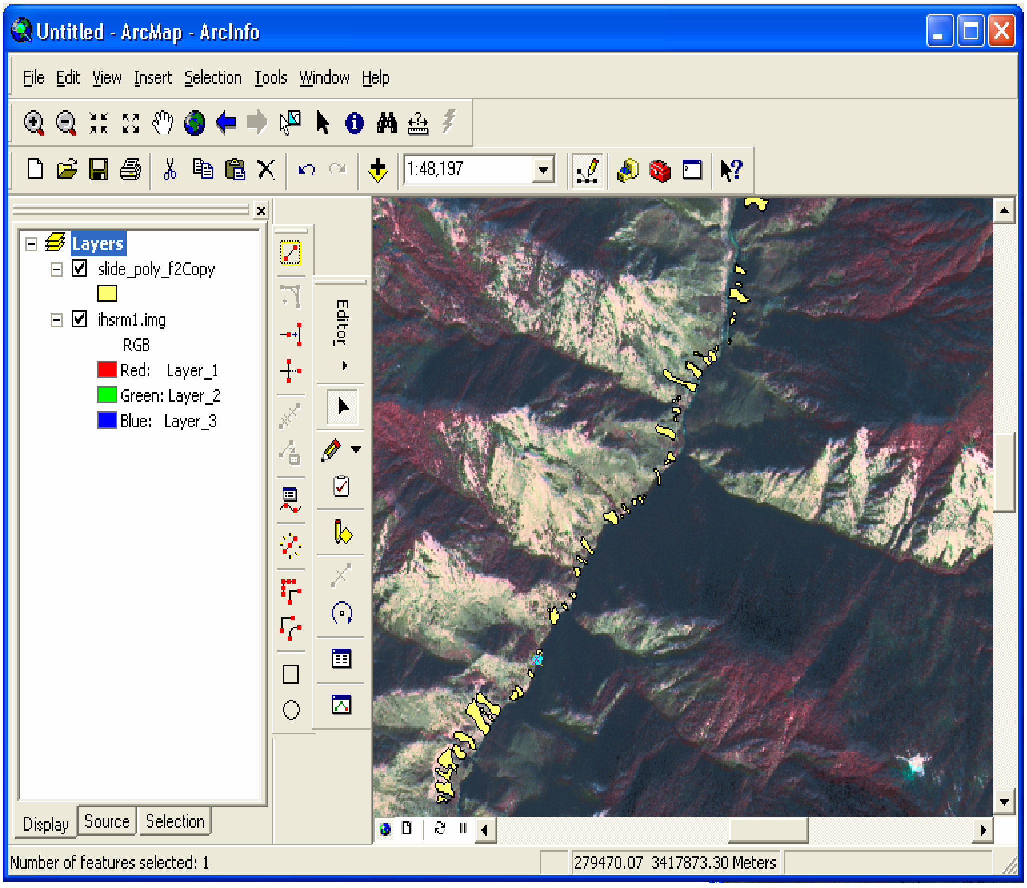


Figure 5.9: Showing the Screen Digitization of landslides on Liss4 MX Image

Snapping option was set at end edge and vertex during digitization. The digitization of slides was done in polyline mode and afterwards transformed in to polygons by a tool called Feature to Polygon available in Feature Tool Box. Software automatically generates IDs for each slide. But separate IDs are given to each slide keeping a relation to increasing kilometer location along the roadway.

After creation of the shape file for landslides the attributes are added. Attributes like Location_id_km; Slide_id, Activity, Sl_type; No_occurre_ are given according to the data collected during pre-field institutional survey and field survey session and Area, perimeter, have been calculated with the help of field calculation tool available in the software. To calculate the length of road affected by slides, the polygon layer of slides is overlaid with the road layer by Intersect Tool, the resultant output gave a line layer with sections having the road length affected by each slide. Those values are finally copied to fill up the column called “len_rd_aff” in the landslide attribute table. Thus the digital database for landslides has been generated. These landslide data base is only for the slides those touching the NH 108. Slides not in contact with the road are being not included in the data base.

Attributes of Landslide_final_poly_5NOV

FID	Shape*	Loca_id_km	Slide_id*	Sl_type	Activity	No_occurre	Area	len_rd_aff
1	Polygon	56.3	1	Debris slide	Active slide	2	3795.24041	42.097
2	Polygon	57.1	2	Rock slide	Old slide	1	948.95952	27.496
3	Polygon	57.125	3	Rock slide	Old slide	1	1000.91864	33.289
4	Polygon	57.2	4	Rock slide	Old slide	3	983.68195	56.11
5	Polygon	57.3	5	Rock slide	Old slide	2	4266.23651	50.995
6	Polygon	57.7	6	Rock slide	Old slide	1	3866.13947	80.223
7	Polygon	57.9	7	Rock slide	Old slide	1	6460.74538	81.296
8	Polygon	58.2	8	Rock slide	Old slide	1	4447.64651	56.208
9	Polygon	58.5	9	Debris slide	Old slide	1	9066.38111	115.123
10	Polygon	58.8	10	Debris slide	Old slide	1	1323.44232	56.54
11	Polygon	59.05	11	Debris slide	Reactivated slide	4	5581.63761	74.988
12	Polygon	59.18	12	Debris slide	Old slide	1	966.43742	20.489
13	Polygon	59.4	13	Debris flow	Old slide	3	854.09067	35.167
14	Polygon	59.6	14	Debris slide	Old slide	2	1933.34422	33.806
15	Polygon	59.8	15	Debris slide	Old slide	2	963.56398	36.03
16	Polygon	59.9	16	Debris slide	Old slide	4	6078.81198	50.586
17	Polygon	60.9	18	Debris slide	Old slide	4	1028.6343	49.182

Record: 1 Show: All Selected Records (1 out of 83 Selected.) Options

Table 5.3: Showing attributes database creation in ARC GIS 9.1 for the landslide layer

In order to correlate each slide with various dates of occurrence in last twenty five years an additional table called “landslide _final_table” was created and joined with main landslide table. The table join was done on the basis of one common field called “Sl_id” which is basically the primary key (the field which can uniquely identify each entity) in the main landslide database and is used as foreign key in the second table and therefore being repeated against slides having more than one occurrence date. The main table of slide is therefore related with second table after joining. In this second table all the date information along with other information of the main landslide table can be viewed and attribute query regarding the dates can be performed.

Attributes of landslide_final_table1

landslide_final_ta	landslide_final_table1.Slide_id	landslide_final_table1	Landslide_final_poly_5NOV.Loca_id_k	Landslide_final_poly_5NOV.Sl_type	Landslide_final_poly_5NOV.Activity	Land
0	0	<Null>	0			
1	5	8/12/1998	57.3	Rock slide	Old slide	
2	5	8/13/1998	57.3	Rock slide	Old slide	
3	6	8/1/2004	57.7	Rock slide	Old slide	
4	7	8/20/2000	57.9	Rock slide	Old slide	
5	8	8/8/2004	58.2	Rock slide	Old slide	
6	9	8/7/1998	58.5	Debris slide	Old slide	
7	10	8/2/2000	58.8	Debris slide	Old slide	
8	3	12/20/1988	57.125	Rock slide	Old slide	
9	1	7/2/2007	56.3	Debris slide	Active slide	
10	1	7/4/2007	56.3	Debris slide	Active slide	
11	2	8/12/1998	57.1	Rock slide	Old slide	
12	4	8/11/1998	57.2	Rock slide	Old slide	

Record: 1 Show: All Selected Records (4 out of 281 Selected.) Options

Table 5.4: Showing the repetition of slide Ids against more than one occurrence date associated with one slide location.

Finally as shown below the digital inventory for the landslide along the NH 108 is prepared which is specifically describing the various types, date, size, of the of landslides occurred in the study area. As this is one of the sub-objectives of this research work therefore the detailed discussions will be done on chapter 5. Preparation of this landslide inventory is used as a tool to assess the principal objective of determining the temporal hazard rate.

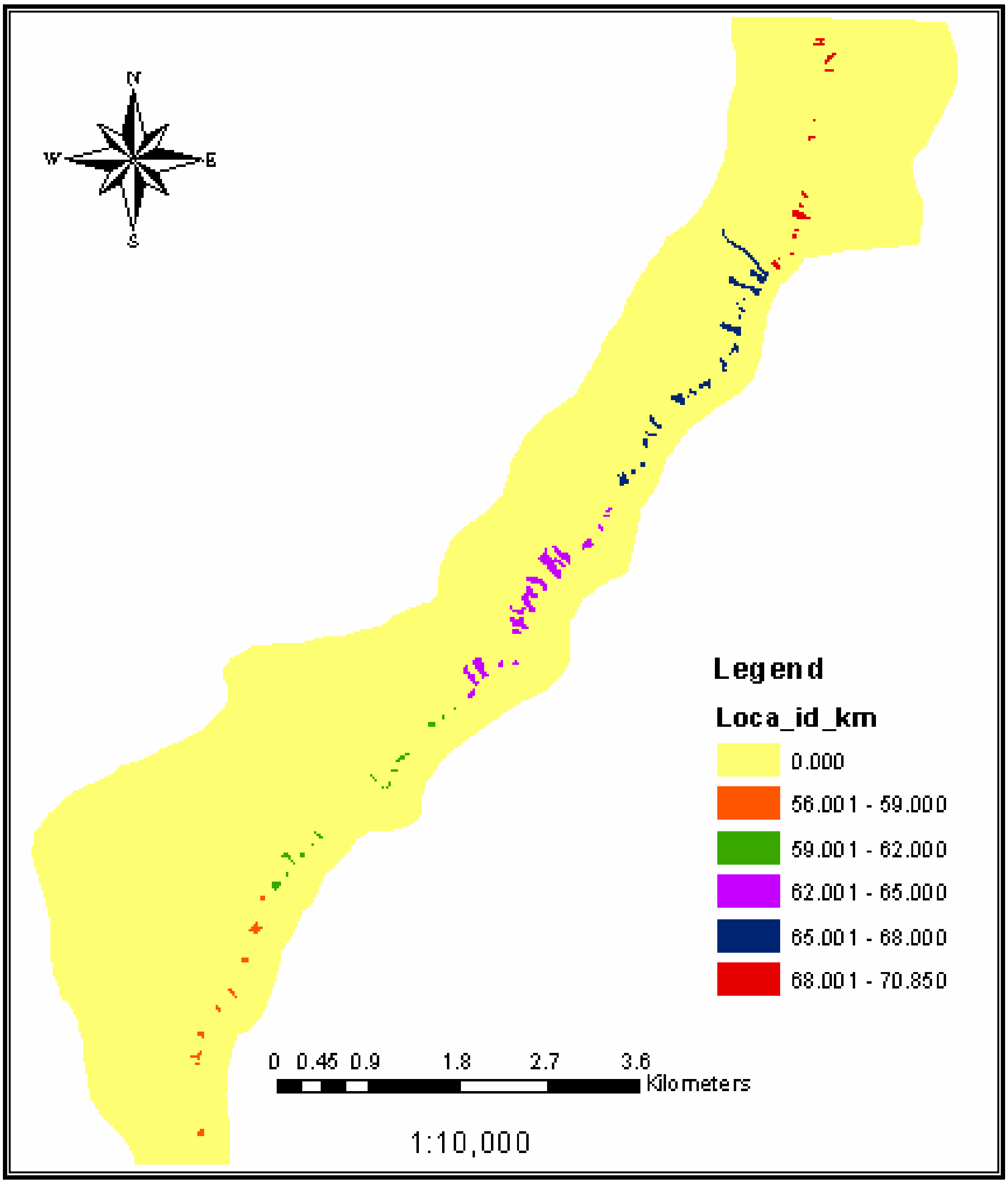


Figure 5.10: showing the distribution of landslides between Bhatwari to Gangnani on NH 108 road corridor

5.2.3.2. Geo-environmental Factor Map Preparation:

To derive the homogeneous units of the road corridor factors related to the terrain conditions and first order geological conditions are taken into account. These are Lithology and Slope. In the year 1999 according to plan implemented by government of India a LHZ mapping was carried out in this area along the road corridor in the year 2001 using Analytical Hierarchical Process (AHP) technique developed by (Saaty, 1980). Fourteen terrain parameters were considered for the analysis and LHZ map was prepared for the study and those are generated in IIRS itself.

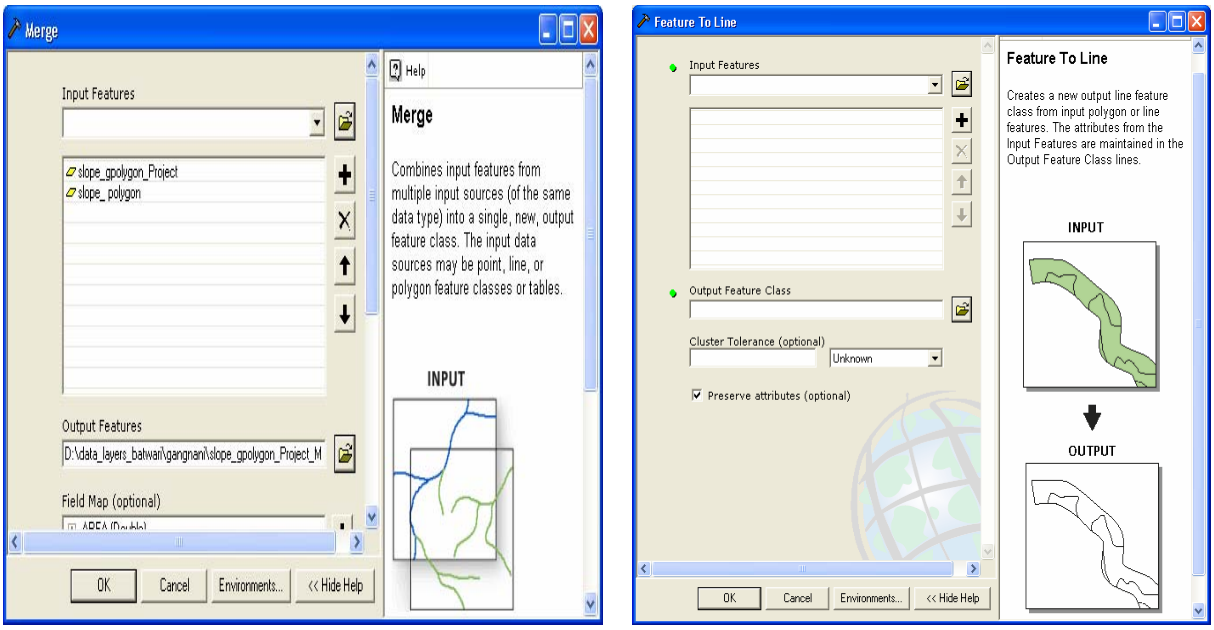


Figure 5.11: showing the various Data Management operations done to obtain geo-environmental factor layers

Among those factors Lithology and Slope have been considered for extraction of homogeneous sections of road. The factor maps were available for the study area but as separate adjacent sections. Therefore it was necessary to combine the in to one layer. This has been done through merging of two adjacent layers of same factor by Merge Tool.

Figure 5.12: showing the gap in the merged slope layer and right –Showing the final slope layer generated after completion of vector editing in ARC Map 9.1.

After merging, two meters gaps between the polygons lying at boundary were found as shown in the figure 5.12. To remove these gaps in the merged layer a lot of vector edition has done. Each of the polygons at boundary lying apart by two meters are made properly overlapped and adjacent

Polygons having same attribute are merged in to one with Merge option provided in Editing Toolbar. All these editing are done in a line layer derived through of conversion polygons to line, using Feature to Line Tool. Finally the layer with corrected topology has been converted to polygons once again which did not keep the associated attributes intact. As obvious the attributes are again added very carefully to the final layer for both the Slope and Lithology units.

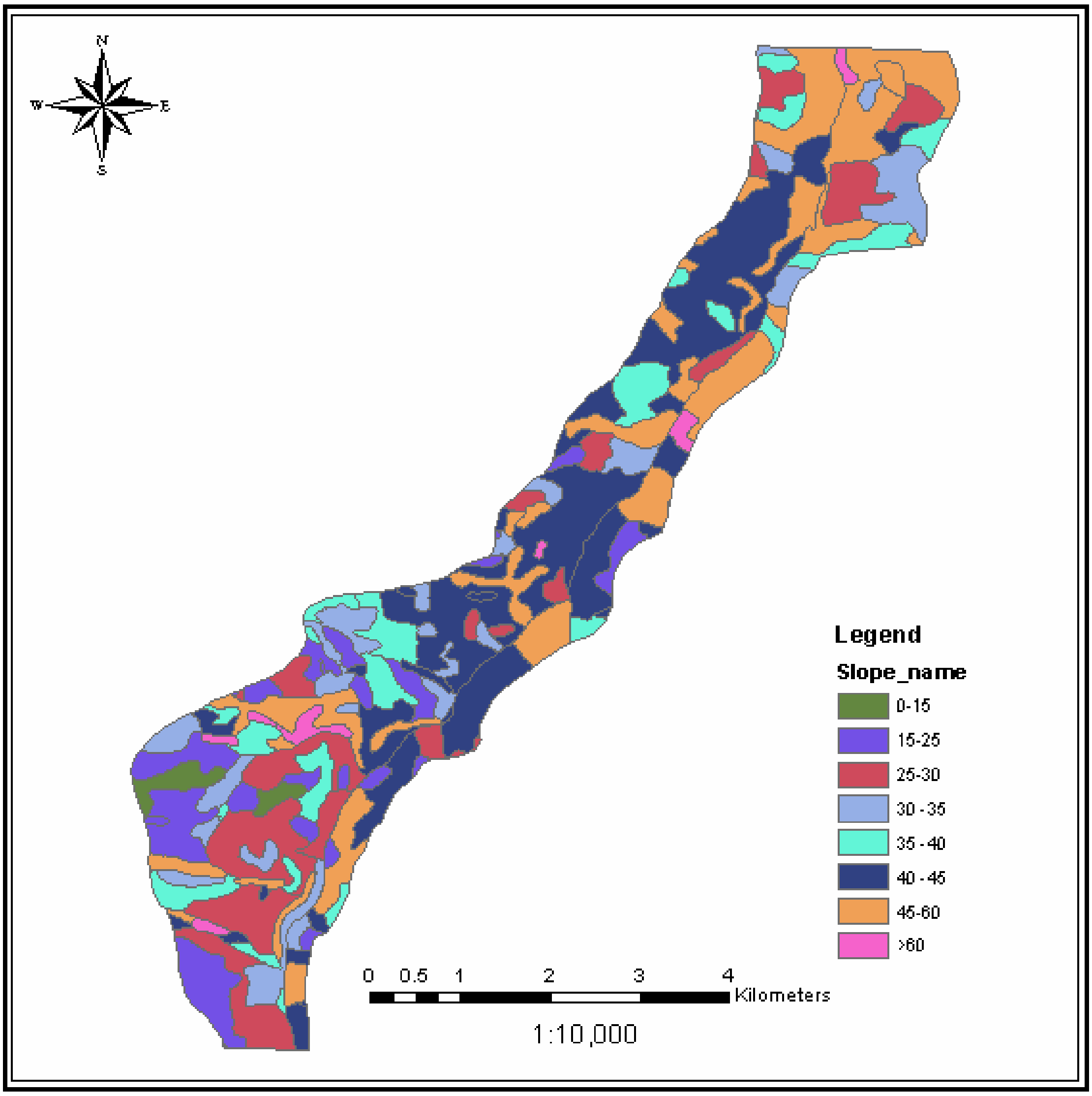


Figure 5.13: Showing various slope units of the study area.

the amount of slope in the study area is classified into eight slope units ranging from 0-15, 15-25, 25-30, 30-35, 35-40, 40-45, 45-60 and >60. The lithological mapping of this area was done on the basis of first order geology and therefore three main classes are found like Gneiss, Schist, and Unconsolidated Sediments.

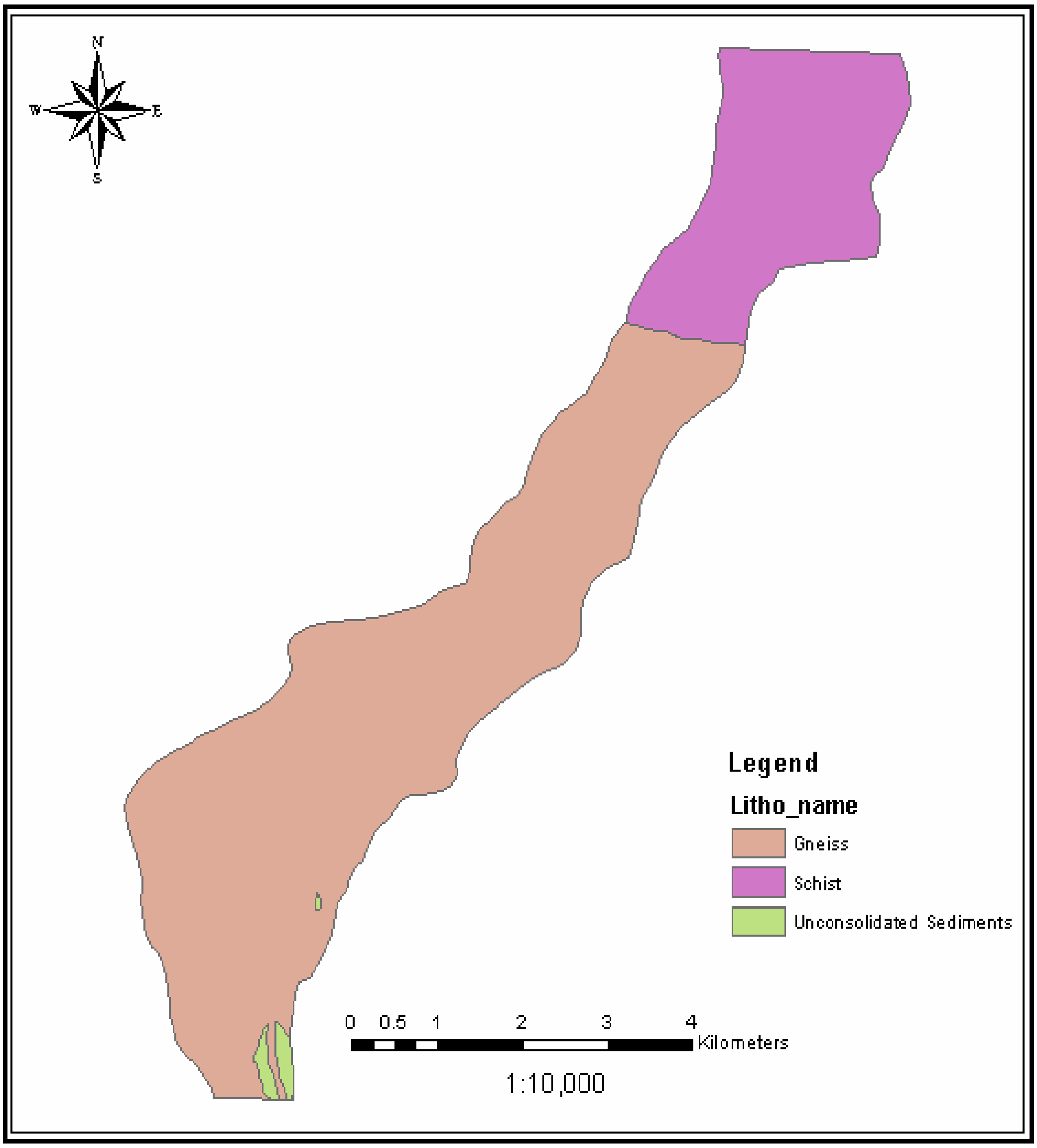


Figure 5.14: Showing the lithological units of the study area

5.2.3.3. Extraction of Homogeneous Road units on NH 108:

To obtain the homogeneous road units the unique condition units (UCU) were taken into account based on lithology and slope situation of the road under study (Van Westen et al, 2000). This is also known as Conditional Analysis Method (Clerici et al, 2002) where the factors contributing to instability of landsurface are taken into account in order to divide the territory in to unique condition units. Here the lithology and the slope layers are overlaid by Union Tool in order to extract the unique conditions which is a polygon output with each polygon indicating the slope and lithological conditions prevailing in the study area. Therefore the road layer is once again overlaid with the Unique Condition Unit layer to derive a segmented line output where each section of the line belongs to a separate unique condition unit. The attribute table of the resultant line output i.e. is in fact the roadway shows the lithology and the slope class through which it passes.

Thus the homogeneous geo-environmental road units are derived which is rather a sub-objectives of the present research work. Therefore it will be discussed later in detail in the chapter 5. As final outcome of 41 road section are found. These are the final mapping units along the road on which the temporal probability of landslides will be assessed further.

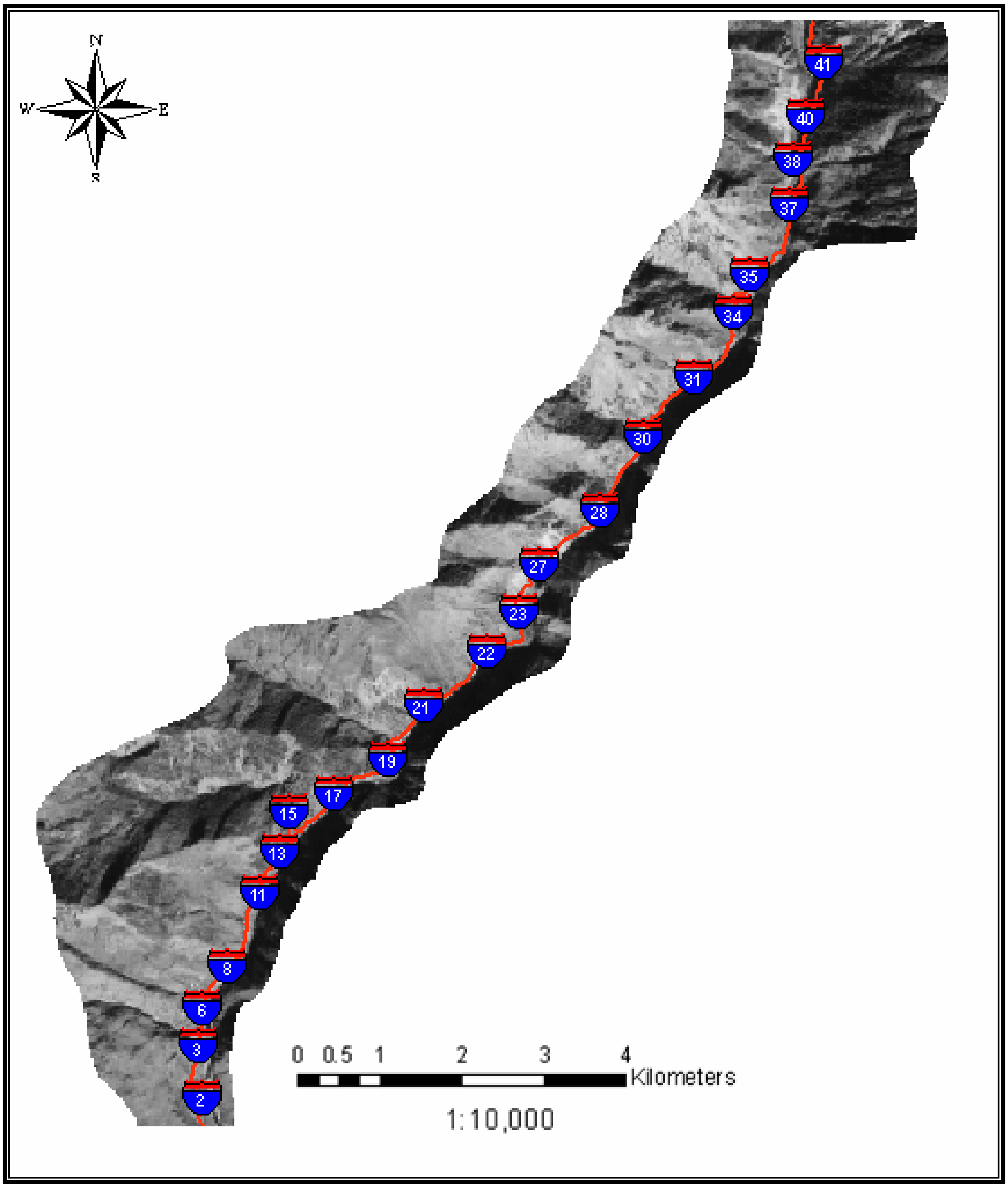


Figure 5.15: Showing the 41 road units derived on the basis of homogeneity on NH 108

6. Results and Discussion:

This chapter describes the output of the present research in a detailed manner. It provides the illustration over each results followed by necessary analysis as a partial outcome. This chapter mainly throws light on the temporal and spatial risk of a road corridor threatened by frequent landslides, in terms of probability values depicting the hazard scenarios with a quantitative manner. It also enlightens the facts like how estimation of spatial and temporal hazard together can produce better hazard scenarios in case of slope failures.

6.1. Discussoin on Temporal Inventory of Landslides of the Road Corridor:

Estimation of temporal and spatial hazard rate requires an accurate landslide inventory of the roads corridor of interest. Especially temporal hazard rate determination involves a huge amount of reliable information on exact dates of occurrence of each slides event taken place in the corridor route. It is also required to identify and locate each of the landslides occurred in recent past in the field study. Therefore preparation of a temporal landslide database is rather perquisite for estimation of temporal hazard rate.

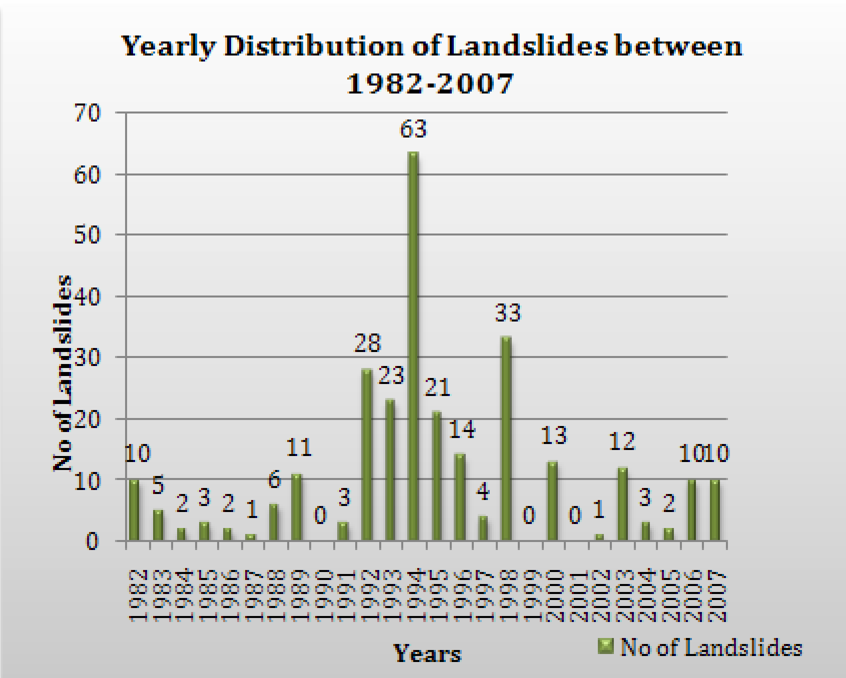


Figure 6.1: Showing year wise distribution of landlides on NH108

The landslide occurrence records collected from BRO during data collection has been arranged in excel sheet. During field observations, each record was verified for its locational existance on ground.

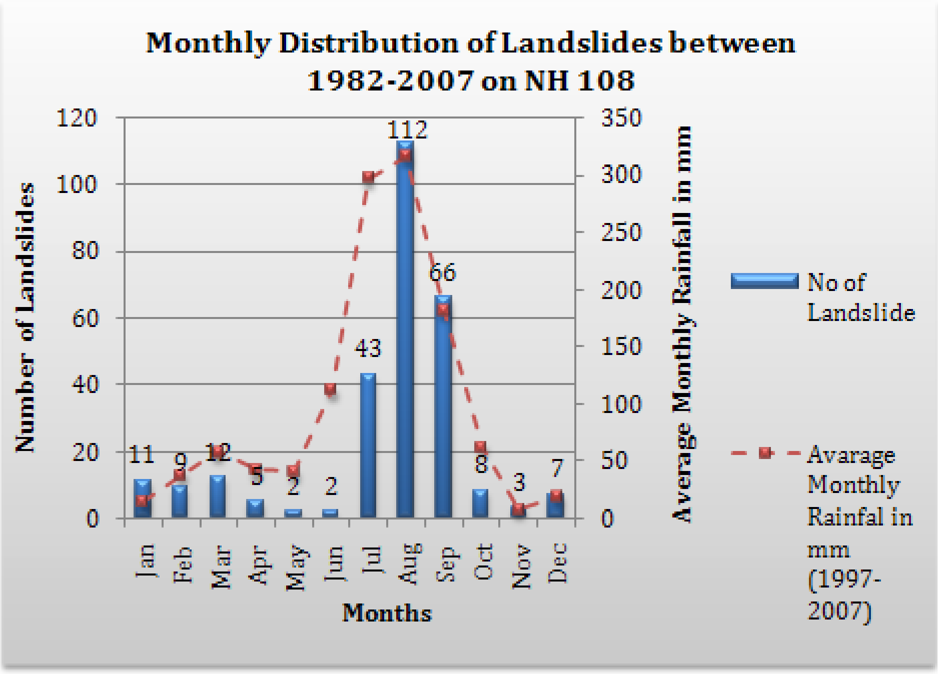


Figure 6.2: Showing the monthly landslide distribution of slides on NH 108

Field verification of slides was done in presence of sector incharges from Boarder Roads organisation who are mainly responsible for providing the lanslide location in BRO records. Therefore the slides of the confirmed locations are only taken into account for preparing the spatial database of slides and further analysis . Preliminary data analysis shows that the majority of the slope failures events takes palce during the monsoon season i.e. July, August and September. These three months had experienced more than 78% of landslides events than the rest part of the year. The rainfall of Bhatwari sector, plotted against the landslide events shows a direct corerelation of failures of the area with monsoonal trigger.

The entire road stretches of 15 kilometres length total 82 landslides have successfully been identified and correlated with the BRO records during field study. These have been classified into several types (Varnes, 1984) according to their state of activity, nature of movement and material involved in sliding observed during field survey. The activity and the slide type maps were prepared for the entire road stretch.

The study area is dominated with debris slides which are found to be around 70.7% followed by 25.6% rock slides and 3.7 % debris flows respectively. Whereas 23.2 % of the slides in the study area are found in an active state because of reactivation of old slides to the fresh slides in the area. Rest of slides are considered in an old state as they did not register any recurrence after the year 2006 up to the time of field survey i.e. 4th November 2007.

Most of the events in the corridor road are found to be single events (69.2%). But there are several multiple events had taken place in one day. Around 19 % of the total events are related to more than 3 failures in a day.

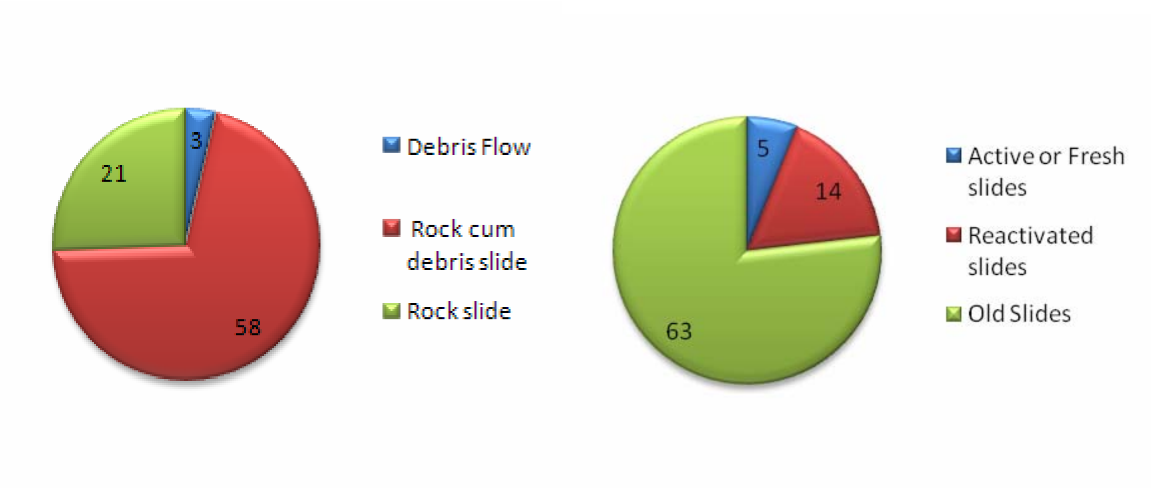


Figure 6.3: Showing number of slides in different slide classes.

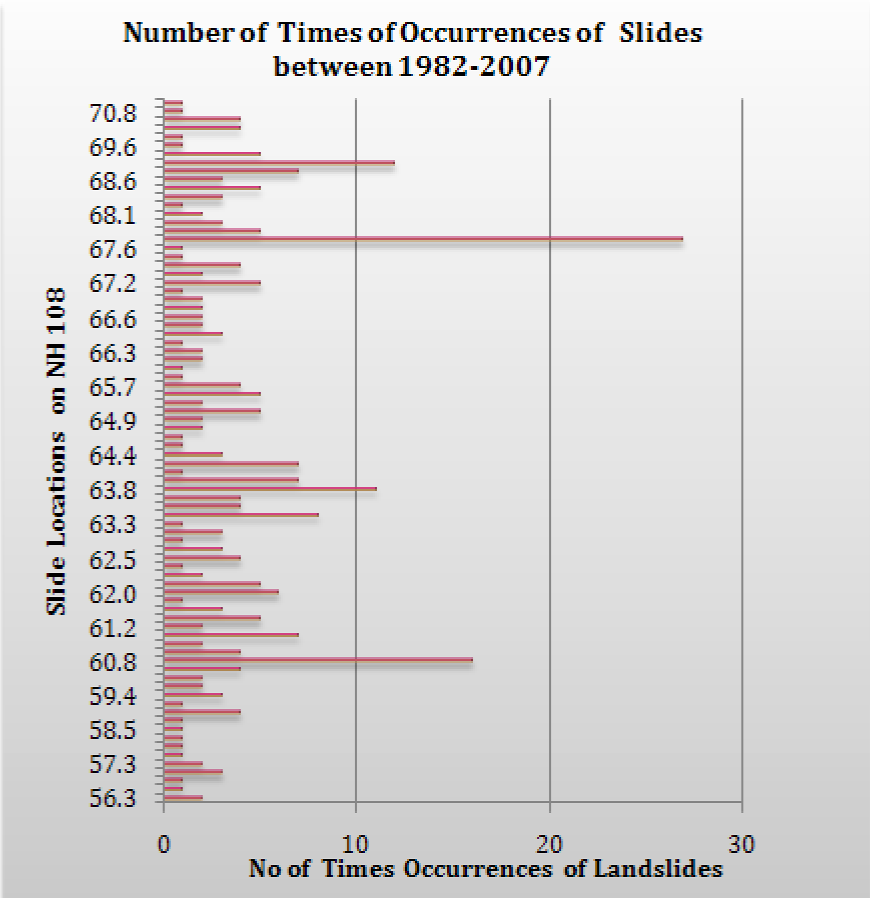


Figure 6.4: Showing the number times of failures occurred at each slides location on NH 108

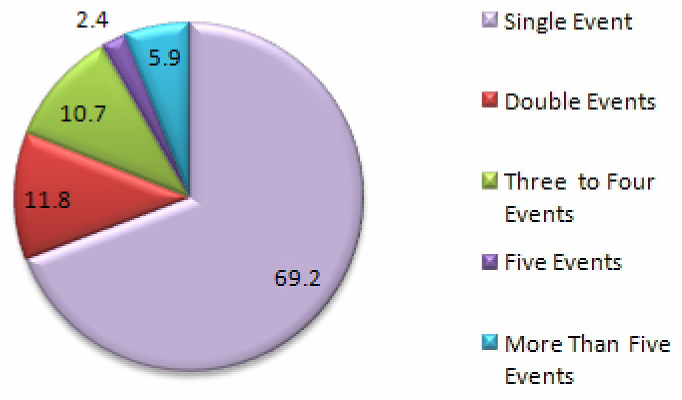


Figure 6.5: Showing the event pattern of the slope failures in a day

6.2. Discussion on homogeneous road units:

Landslides may occur as a consequence of a number of determining and triggering factors (Varnes, 1978). In order to assess hazard from landslides, it is therefore necessary to identify and analyze the most important determining factors leading to slope failure. Depending upon these factors the land surface is partitioned in to different units known as mapping units. For the present research the slope is primarily taken into consideration along with first order lithological conditions in order to derive the suitable mapping units which are in fact the homogeneous road sections according to its slope and underlying lithological conditions.

The road corridor of NH 108 along the Upper Bhagirathi river valley is divided in to 41 road sections which are considered to be the mapping units over the road corridor. The slope condition evaluation of the road section reveals that the majority of these road sections (48.8%) pass through steep slope conditions (> 40 degrees).

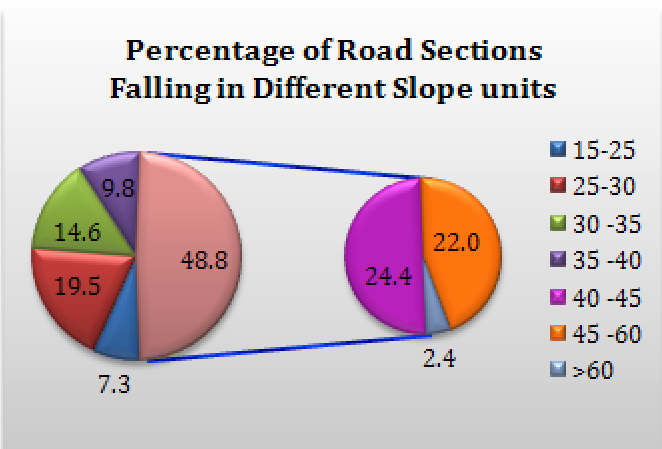


Figure 6.6: Slope conditions of the road units

While investigating the correlation between slope and landslides in the study area it is found in support of the fact that steep slopes are more susceptible to landslides as 77 % of the slope failures on NH 108 have taken place in those steep slopes units between 35 to 60 degrees. And very steep slopes like slopes more than 60 degrees are less prone to landslides.

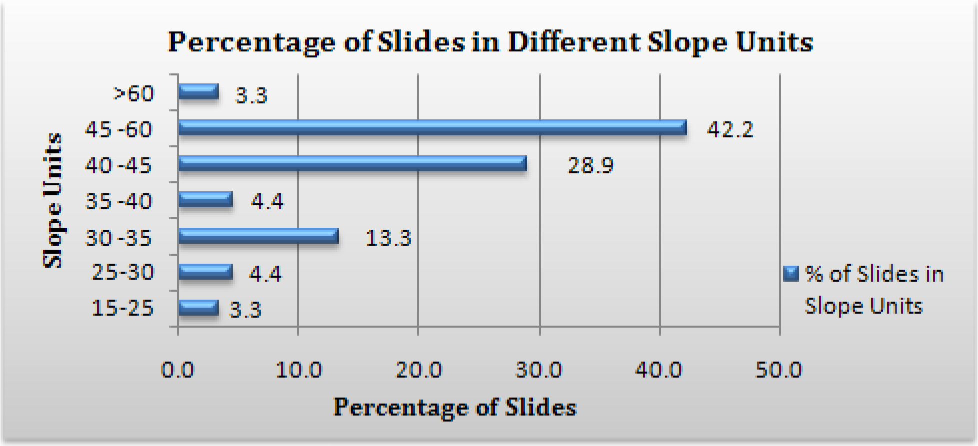


Figure 6.7: Showing the correlation of slope failures with different slope units in the study area.

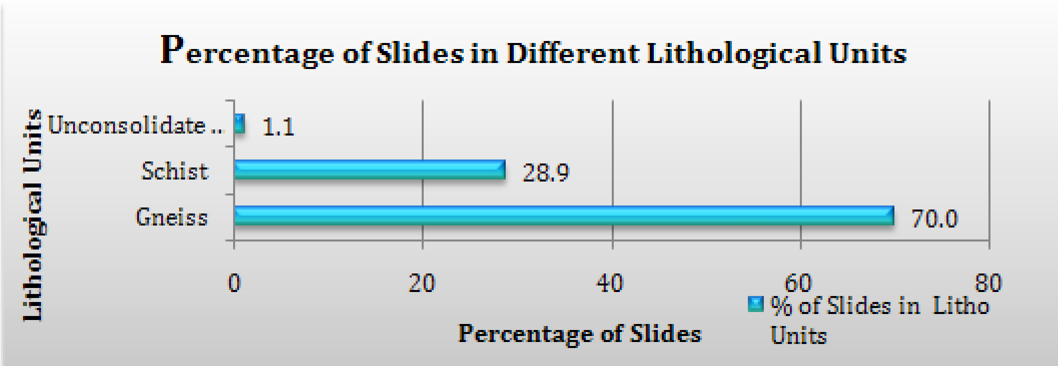


Figure 6.8: Showing the correlation of slope failures with different lithological units in the study area.

6.2.1. Unit-wise landslide distribution:

The frequency of landslides over homogeneous road units was derived to find out the road units having maximum number of landslides. The result shows that road unit 31 situated between km 66 to 67 on NH 108 has experienced maximum number (10) of slides in in past 25 years, followed by the unit 27 having 8 landslides; unit 21 , 22 and 37 having 6 landslides at different locations. When the slope condition was verified through database query revealed that all the road units are passing through similar steep slope conditions lying between 45 to 60 degrees. The underlying lithology is dominantly found to be gneiss at those places. When the spatial susceptibility values of the road units are plotted with number of slides, are almost found to be in accordance with the number of landslides in each unit i.e. high spatial susceptibility in the units having more number of landslides .On the other hand some of the road units having less number of landslides got a high susceptibility value because of their less unit dimension.

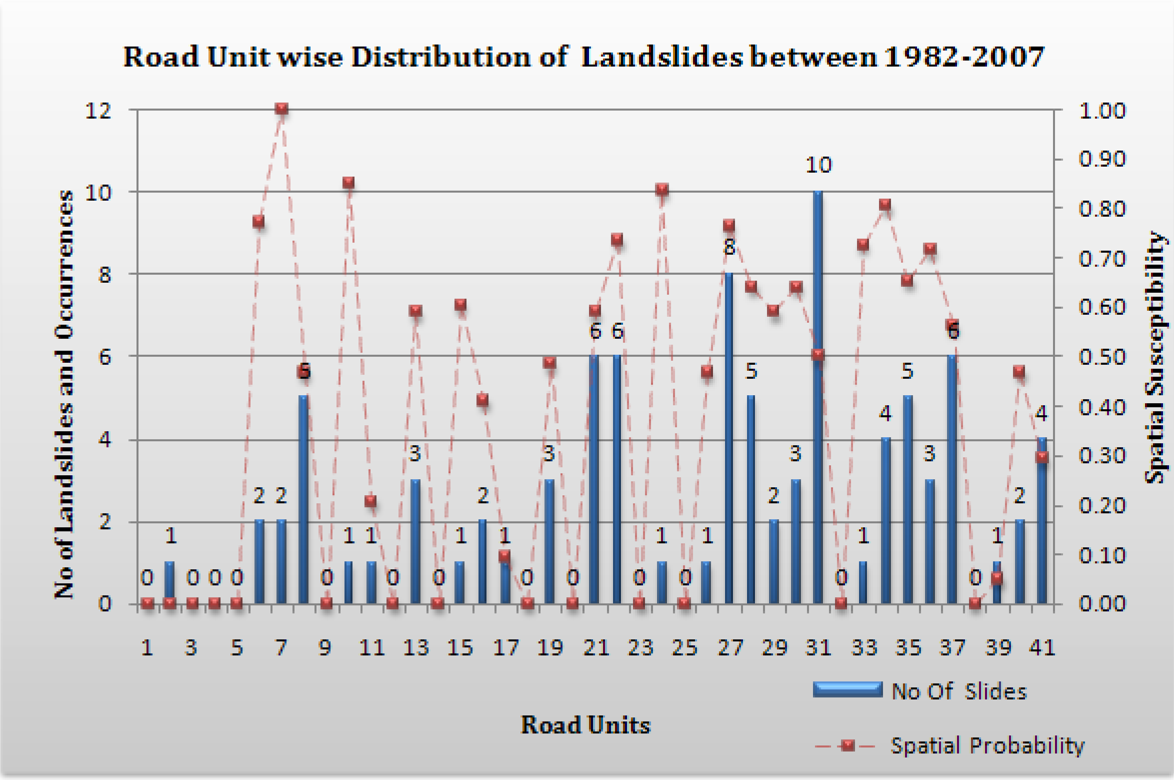


Figure 6.9: Showing number of slides per unit affecting the road corridor.

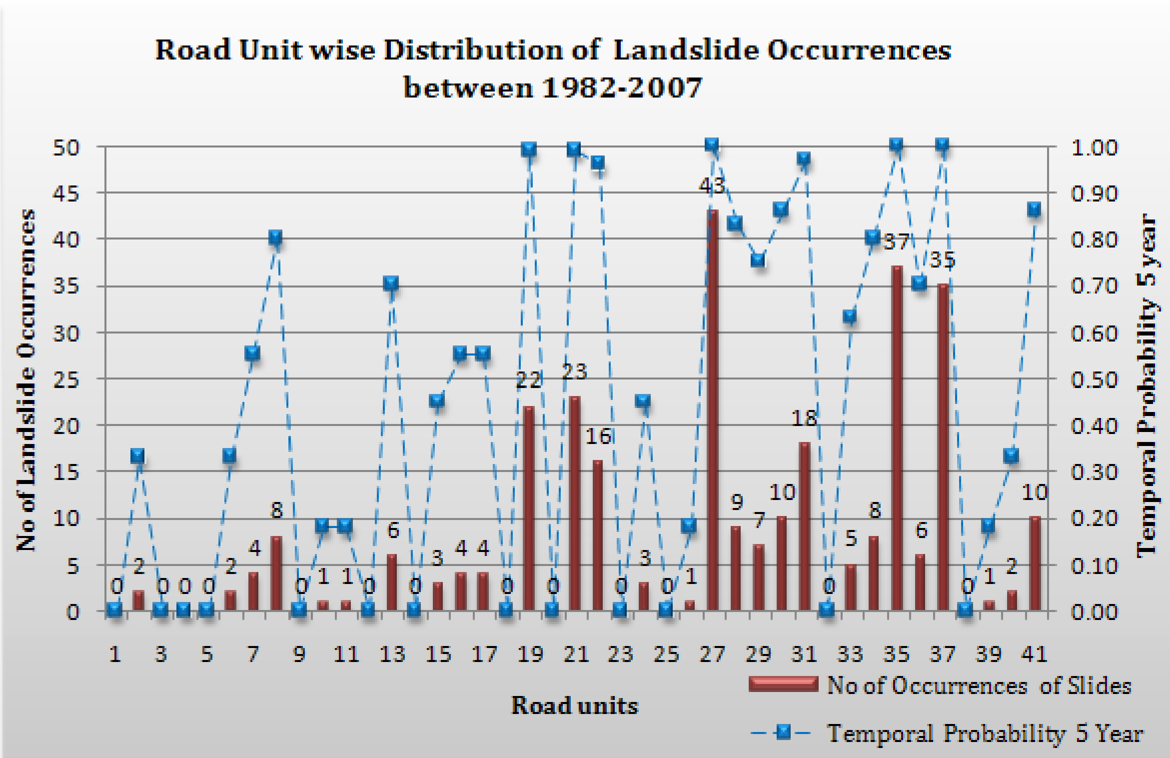


Figure 6.10: Showing number of times of slides occurrences affecting the road corridor

Another similar type of analysis on the occurrence time was done to obtain the landslide frequency of the road units in a temporal domain i.e. the units experiencing landslides maximum number of times in last 25 years. Some of the units having less number of slides for example unit 19 containing only 3 slides had experienced 22 times recurrence in last 25 years whereas unit 28 having 5 landslides, only experienced 9 times recurrence. Consequently the units having frequent landslides rather having more slides in terms of number are more susceptible from temporal aspect to slides. The temporal probability plot gives evidences in support of this fact.

6.3. Frequency of landslide:

The proposed model for landslide hazard requires an estimate of the temporal probability of slope failures. The probability of occurrence of one or more failures was derived unit wise for the entire 15 kilometers road stretch using the Poisson probability model. The basic aim behind the attempt was to assess how frequently the landslides can be expected in the entire road stretch. The calculations are performed in various steps. The first objective was to prepare the current temporal hazard map on the basis of last 25 years data obtained. Further testing the results of the model was also included to assess the predicted hazard scenarios. Therefore another set of calculations are done where only the slides up to 2002 are taken into account and the first set of prediction was done which are validated against the landslides that took place between 2002 and 2007.

To derive the temporal probability at first the the total number of slides occurred in past 25 years have been counted. All the slides fresh, reactivated as well as old slides that can be identified in the field was taken into account to obtain the number of occurrence map of landslides. Therefore it was combined with the road unit map with identity operation and each unit wise number and occurrences of slides are derived. Now the mean reoccurrence i.e. $\mu=1/\lambda$ was calculated and and the exceedance probability of each roads section derived for respective scenarios 1 year, 5 years and 10 years. As per the expectation the temporal probability of experiencing one or more landslides increases with increasing time interval. In the 1 year scenario the less road length is expected to experience landslides but in years and 10 years scenarios almost 90 % of the road length comes under high probability of experiencing 1 or more slides.

6.4. Spatial Susceptibility :

The spatial susceptibility of the road corridor was derived in terms of information value (Yin and Yan, 1988). The susceptibility is the the log of ratio of conditional probability and prior probability. The conditional probability was derived landslide density in each road unit and the prior probability is the landslide density in the entire road stretch. The density of landslide in each unit is derived from the landslide map of the road corridor. The information value was then stretched between 0 to 1 and considered as the spatial susceptibility of the road units.

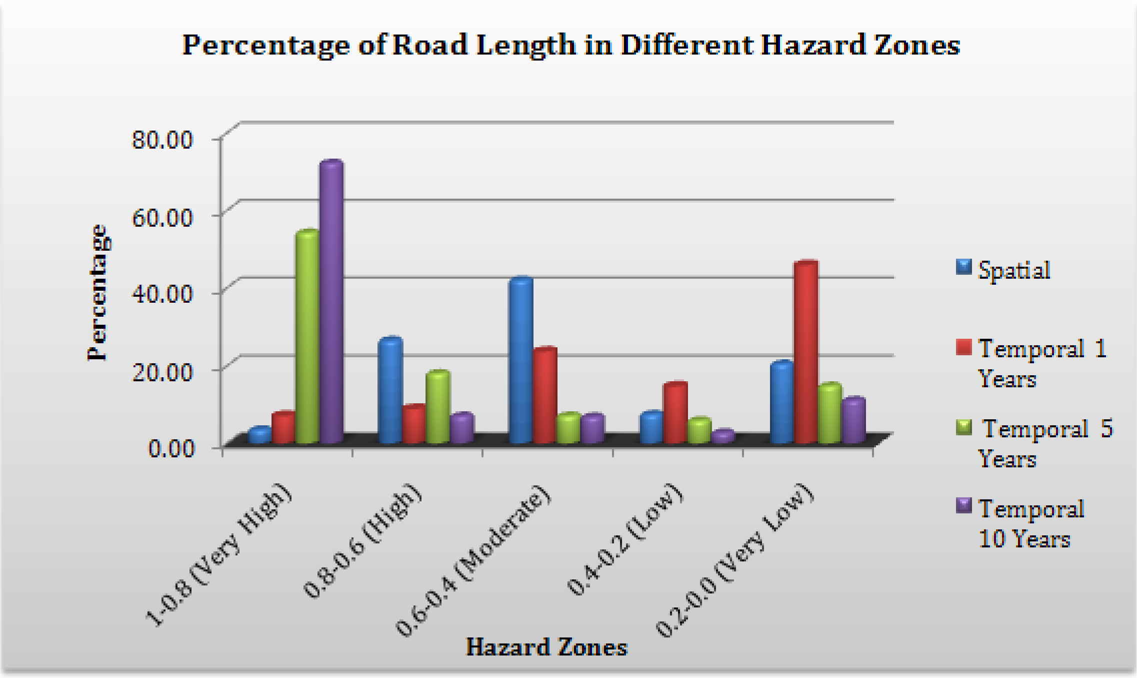


Figure 6.11: Showing the percentage of road affected in different hazard scenarios

The figure above proves that in 10 years scenario almost 70 % of the entire road stretch comes under very high probability of getting 1 or more landslides. Whereas almost 67 % of the entire road stretch is moderate to highly susceptible to slides as far as the spatial probability is concerned.

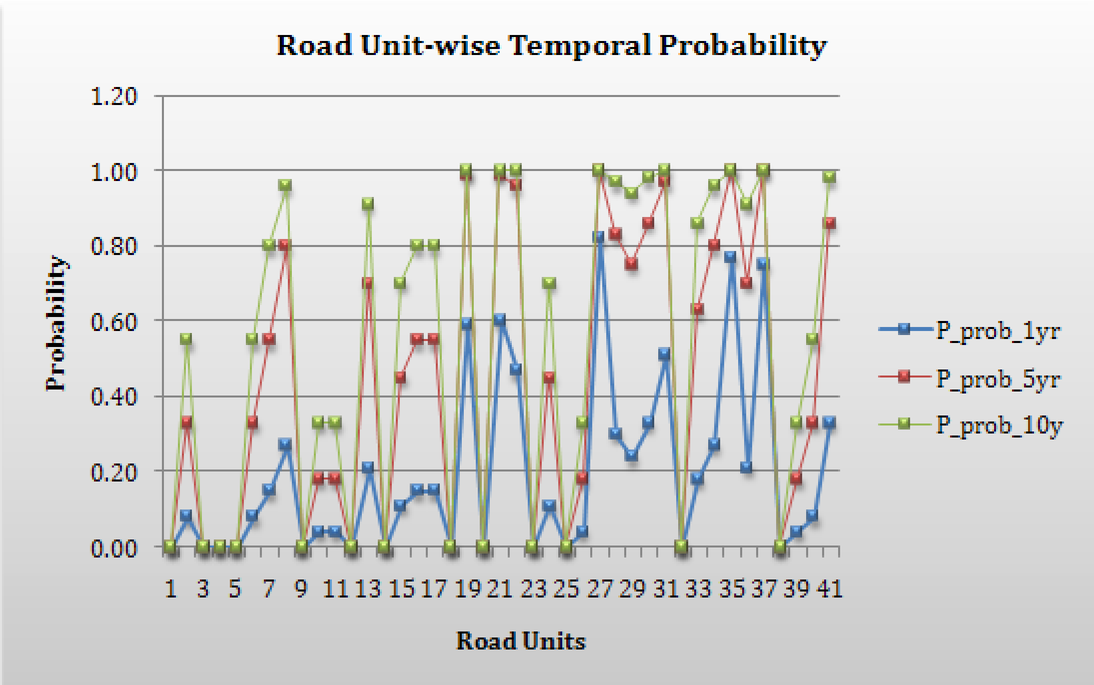


Figure 6.12: Showing increase in temporal probability over time

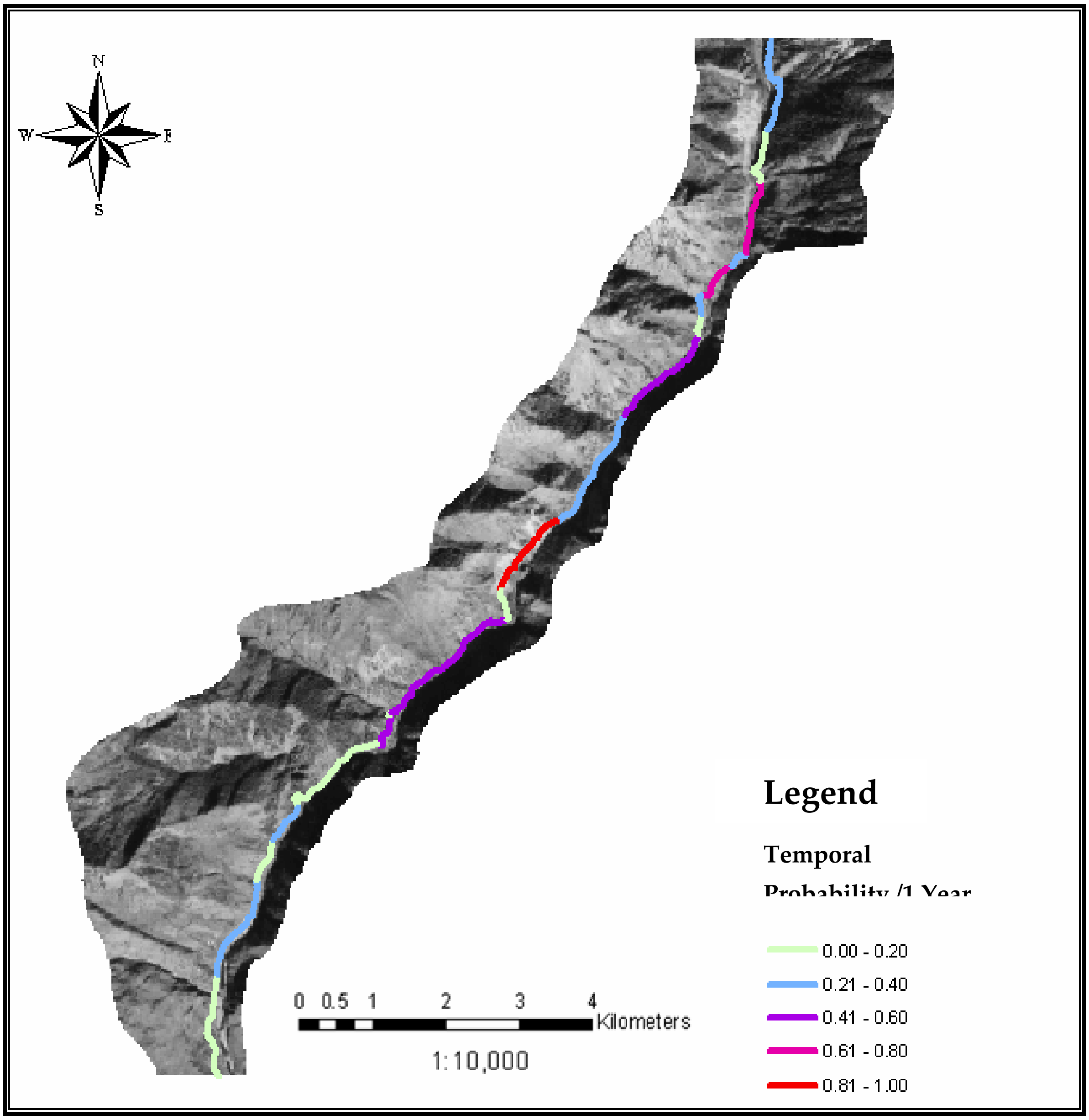


Figure 6.13: Showing the exceedance probability per one year of the road units on NH 108

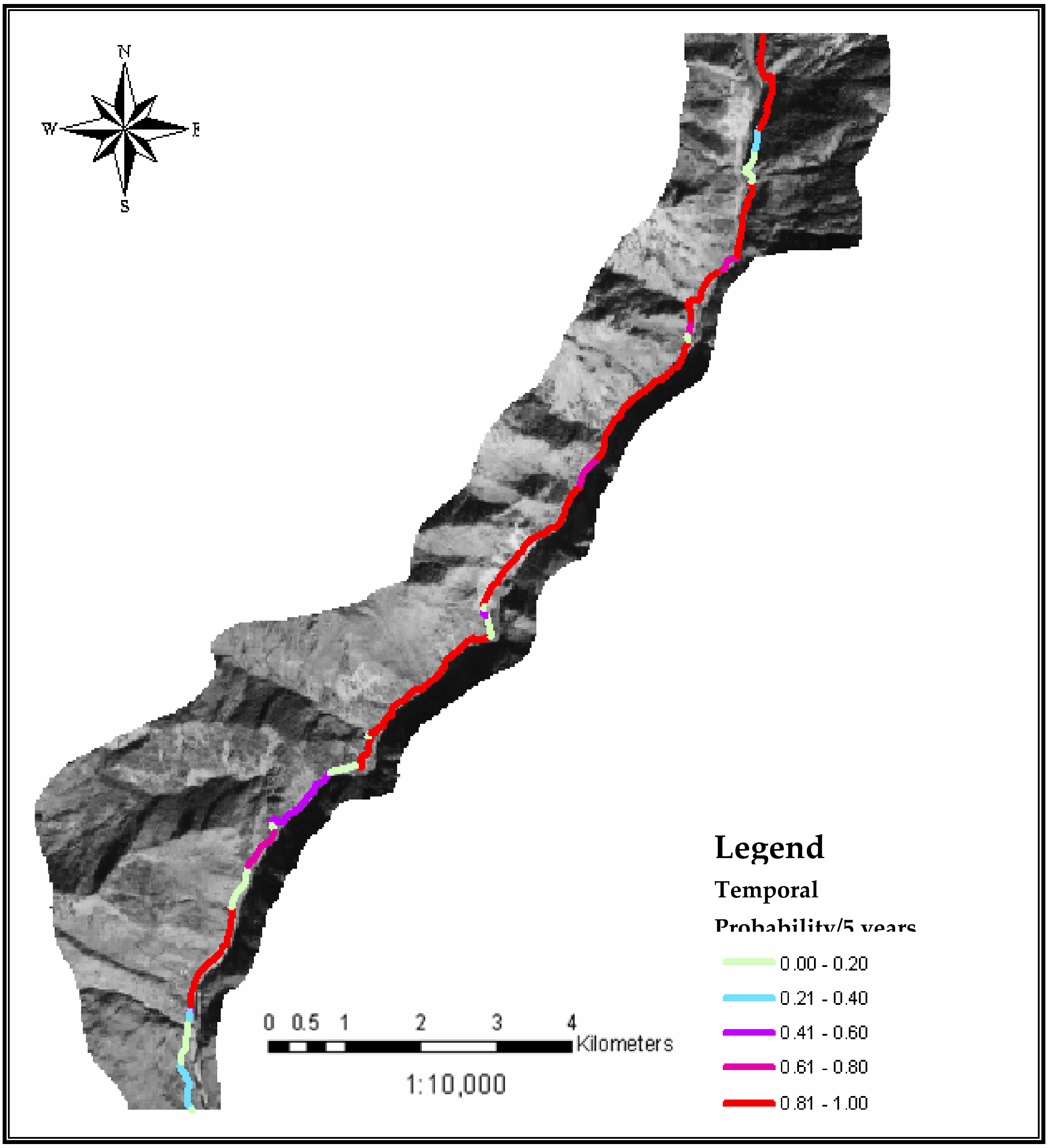


Figure 6.14: Showing the exceedance probability per five years of the road units on NH 108

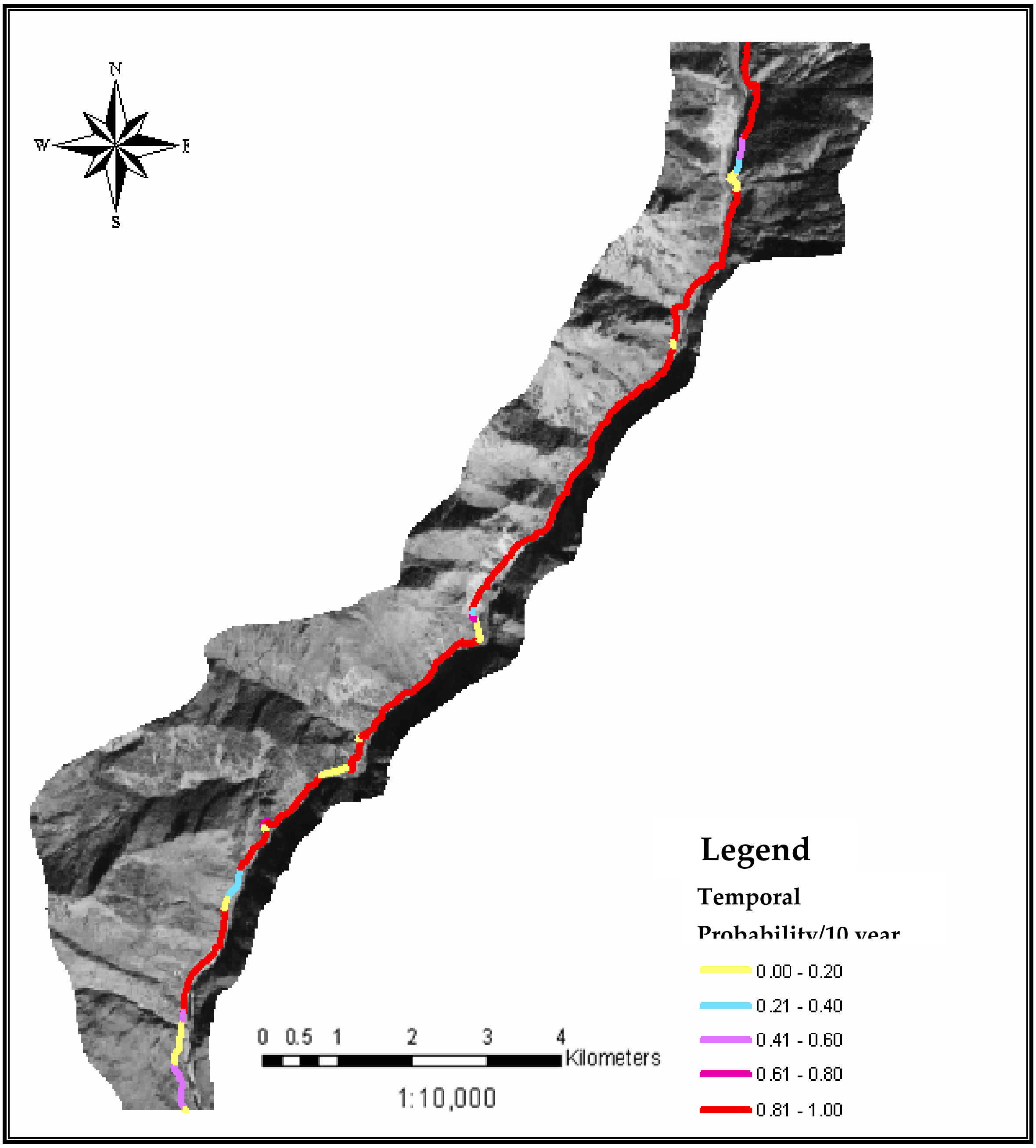


Figure 6.15: Showing the exceedance probability per ten years of the road units on NH 108

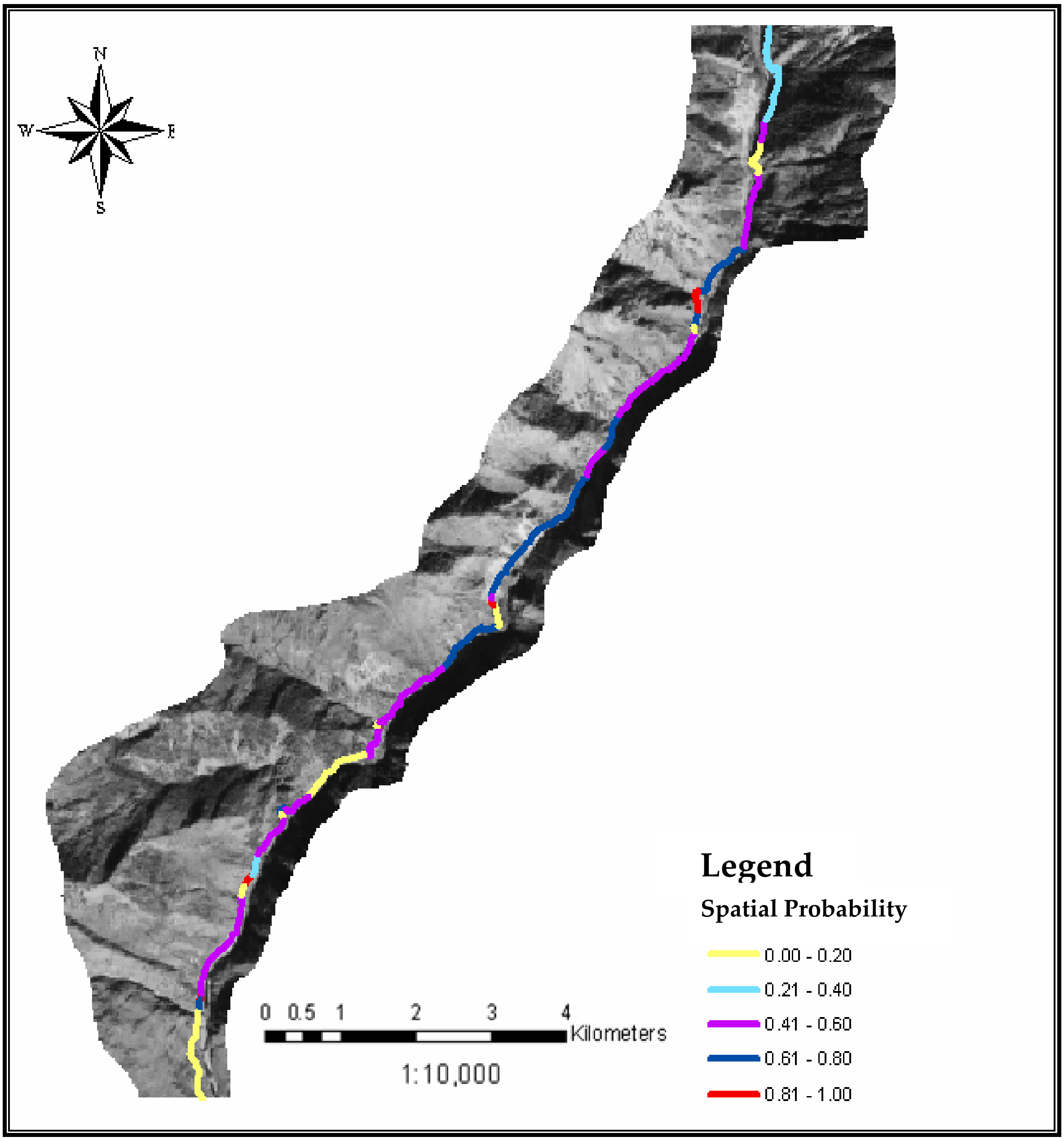


Figure 6.16: Showing the Spatial probability of the road units on NH 108

6.5. Hazard:

The hazard scenarios of different time step were obtained by multiplying the temporal probabilities with the spatial susceptibility of the road corridor. Therefore the hazard is compared with the current active slides on ground for the in order to assess the accuracy of the predicted model.

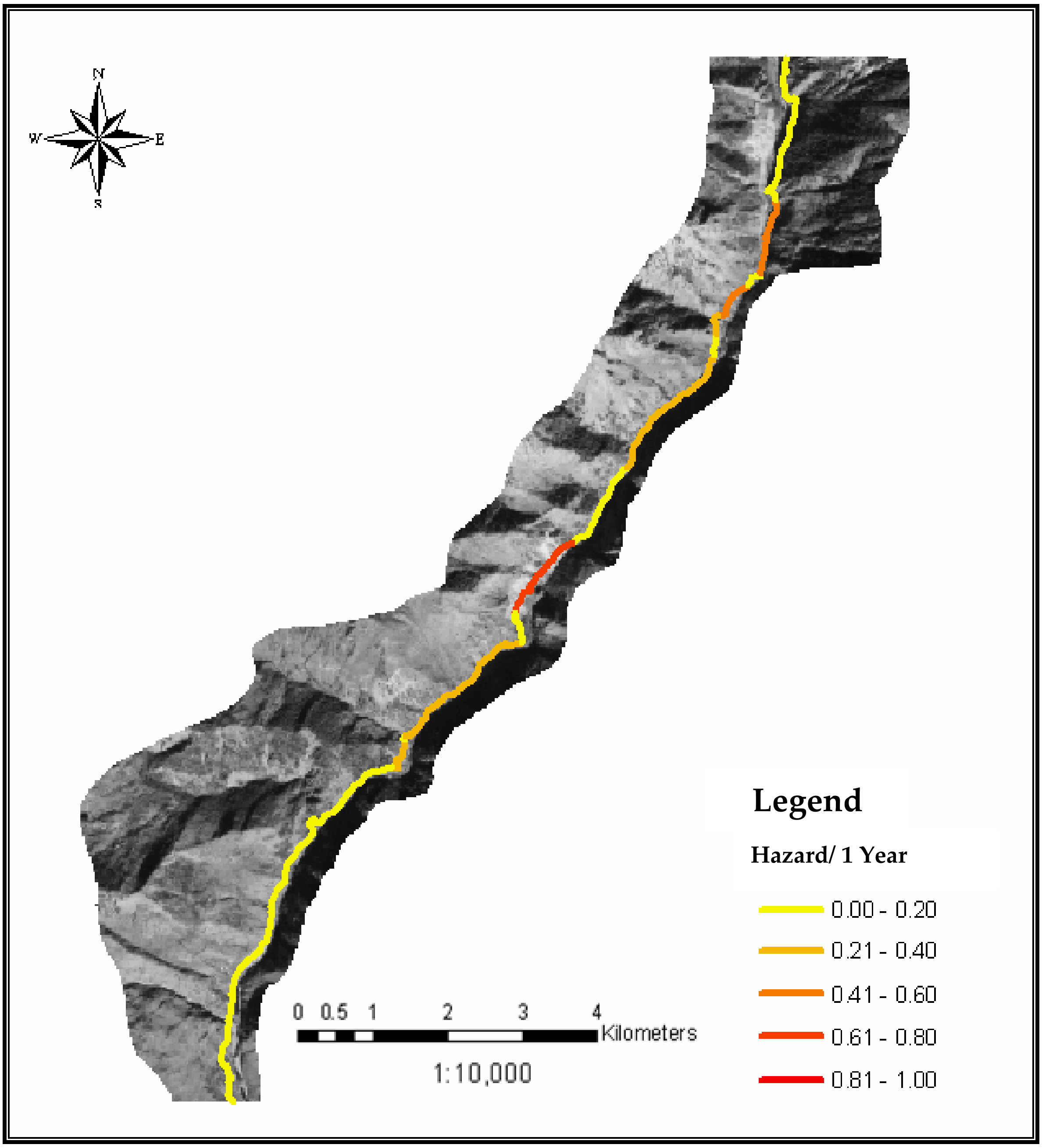


Figure 6.17: Showing the probability per one year of the road units on NH 108

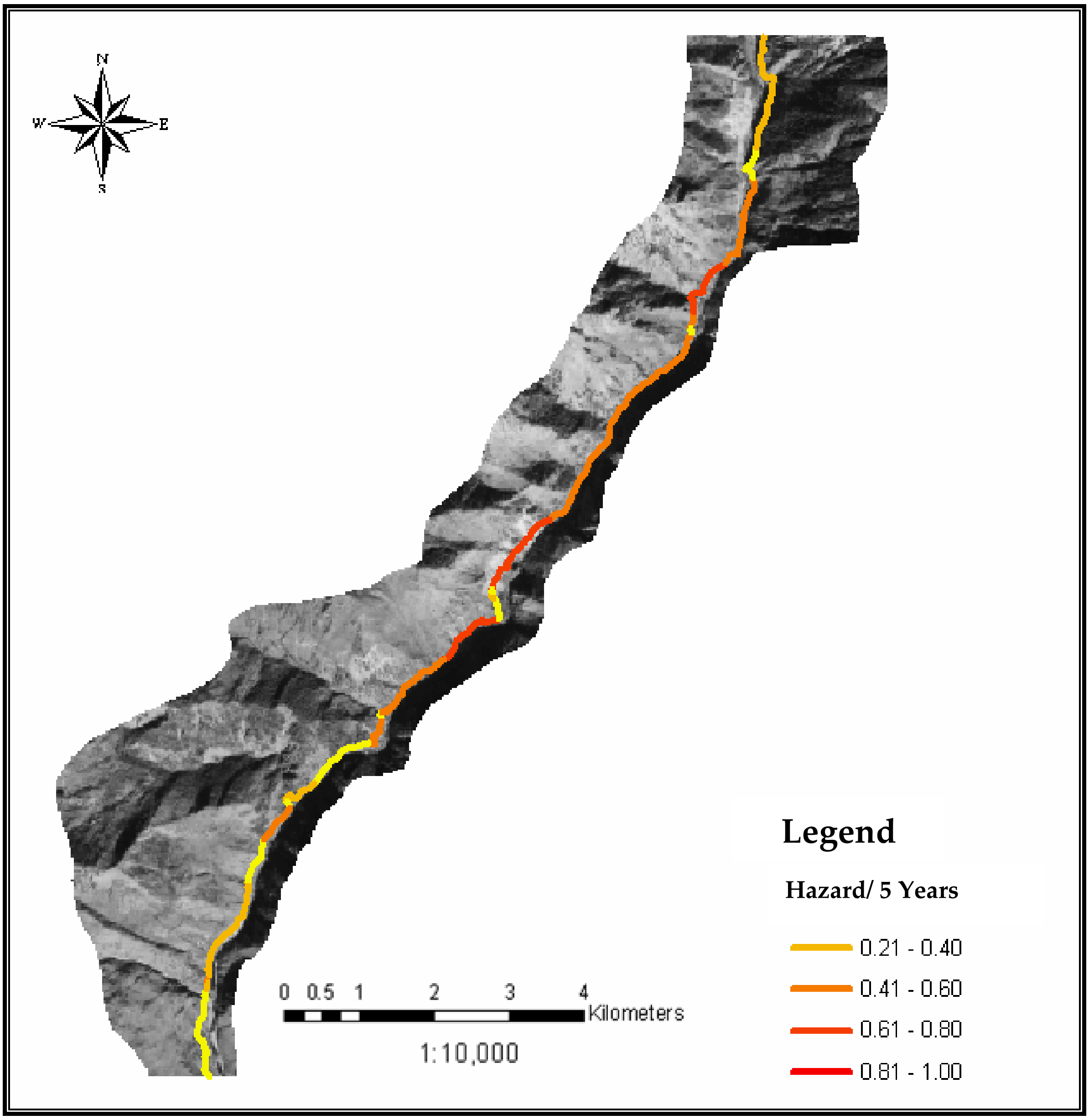


Figure 6.18: Showing the probability per five years of the road units on NH 108

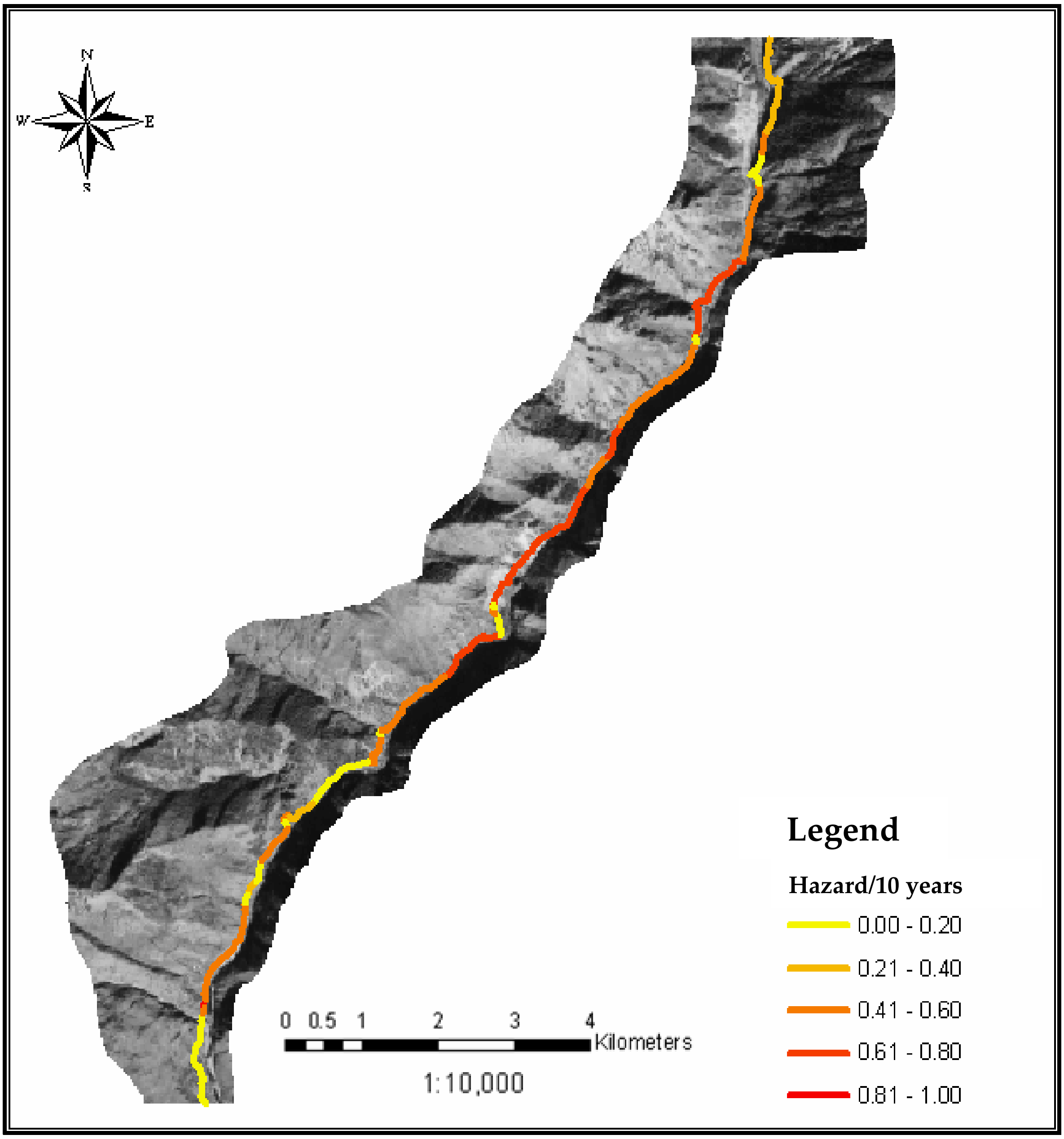


Figure 6.19: Showing the probability per ten years of the road units on NH 108

6.6. Model validation:

The temporal model was checked for it consistency of perdition. For validating the results the data up to 2002 was considered and the probability values are compared with ground results as the data on occurrence of slides 2003 onwards are prepared separately for validation. In this regard validation was only done for 1 year and 5 years scenarios of temporal probability. On the other hand the spatial susceptibility was also validated with respect to the slides occurred during 2003-2007.

6.6.1. Model validation 5 years scenario:

The results shows that 92.9 % slope failures have taken place in high to very temporal probability zones. In terms of number of occurrences 92.5% occurrences belongs to high to very high probability zones. Only 7.2% have occurred in the units having low to very low probability of getting one or more slides in 5 years.

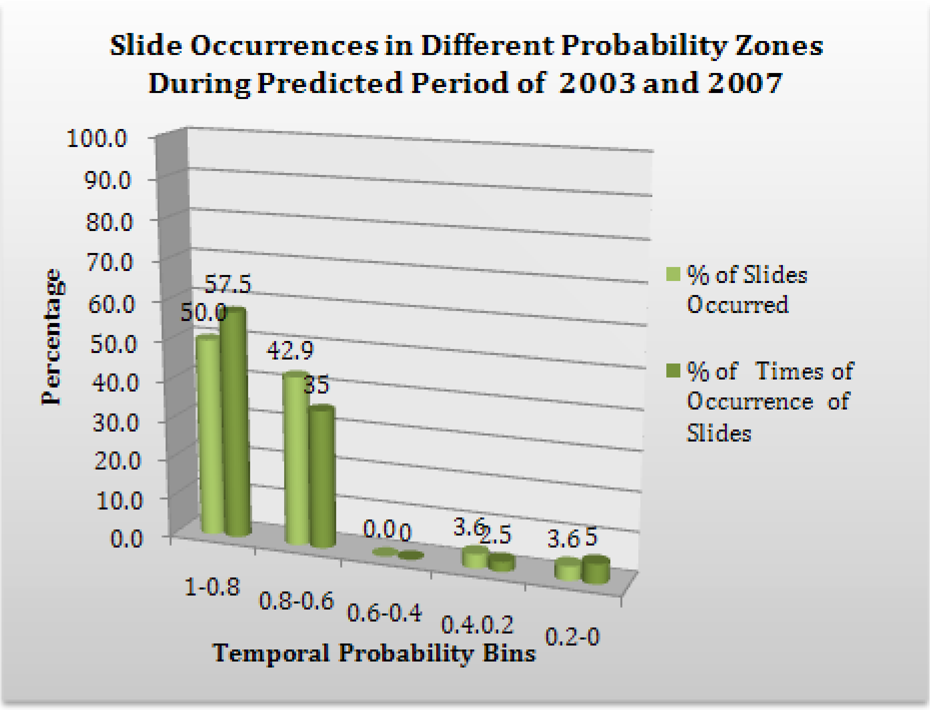


Figure 6.20: Showing percent of landslides in different temporal hazard zones

On the other hand it has also been observed that in case of 5 years scenario the slides had taken place in the units where the spatial probability is also high. Figure 6.21 reveals that 21% of the slides have occurred in high to very highly susceptible units where as 42.9% has occurred in moderately susceptible units and only 35.7 % slope failures occurred in low to very low susceptible units.

The significant fact observed when the temporal and spatial probability values are plotted against each other at each failure, was that in 5 years scenario other than 3.6% of the total events in each case the failure has occurred in temporally high to very high probability units or the units where the spatial susceptibility is contributing highly to the moderate temporal probability values to expect 1 or more slide events.

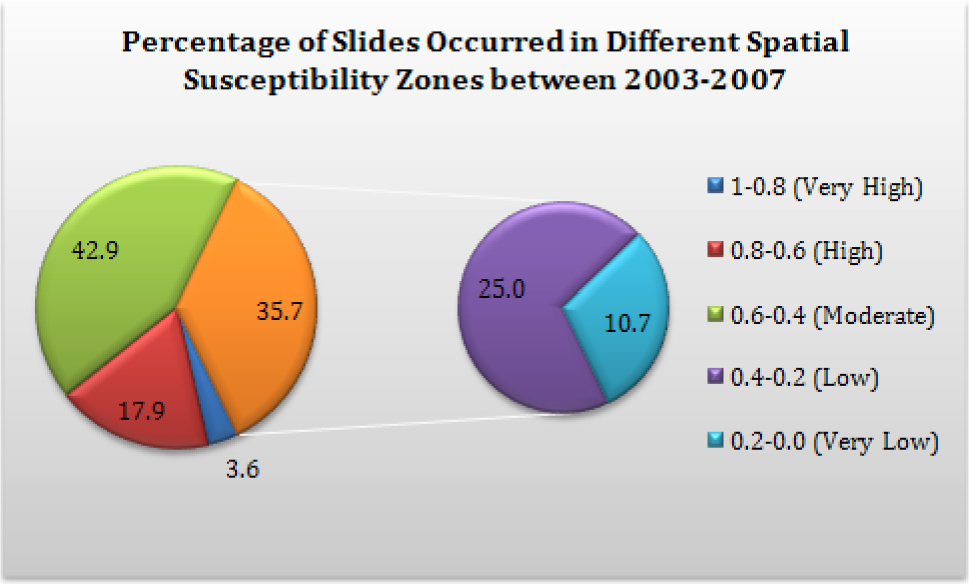


Figure 6.21: Showing percent of landslides in different spatial hazard zones

Fig 6.22 shows that the units having temporal probability more than 0.9 had faced 2 to 3 times failure in 5 years. Almost in 97% cases the failures have occurred in temporal high or in spatial high probability units. And with the increased probability values number of times of failure has also increased.

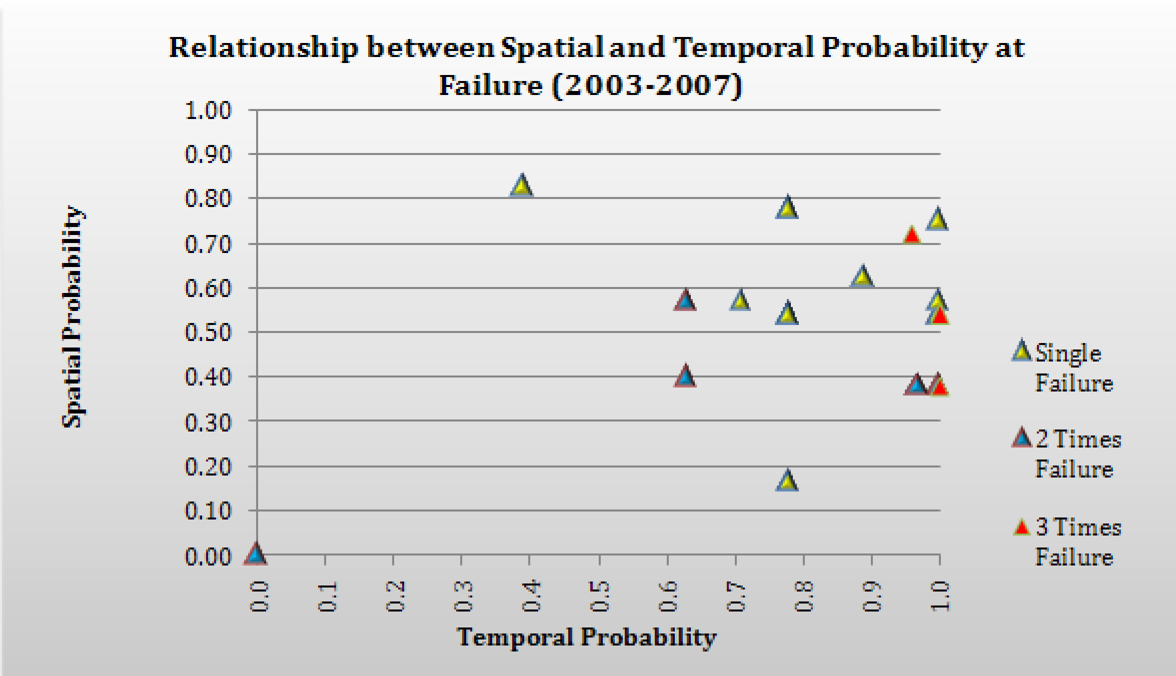


Figure 6.22: Showing relationship between Spatial and temporal probability at failure

6.6.2. Model validation 1 year scenario:

The model was tested for its accuracy for 1 year scenario as well. Both for temporal and spatial probability values are checked for 1 year scenario. For this case three years 2003, 2006, and 2007 were selected for testing the models. The model validation is separately done on spatial and temporal maps because the combined hazard map gets very less hazard values as both spatial and temporal values get multiplied in final hazard.

6.6.2.1. Model validation 1 year scenario (2007):

The 50 % failures of the year 2007 were found to occur in moderate to very high probability units where at the same time the rest 50 % has occurred in the units having low to very low temporal probability.

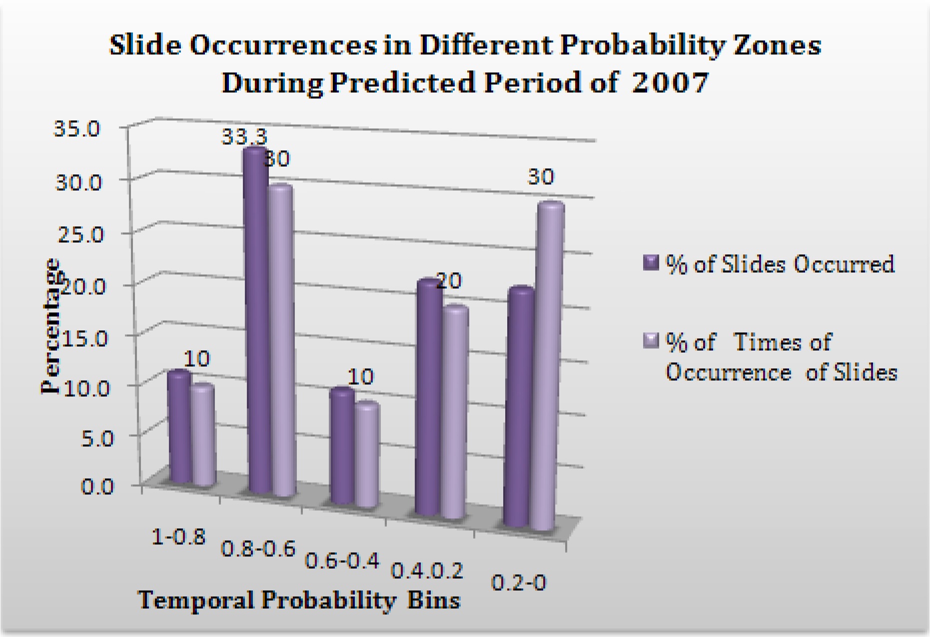


Figure 6.23: Showing percent of landslides in different temporal hazard zones

At same time the 66% of the slope failures has been found occur in the units having moderate to high spatial probability . And rest 33.4% has occurred in low to very low susceptible units.

In case of 1 year scenario the temporal probability is found to predict less successfully as compared to the 5 years scenario. In 1 year the spatial susceptibility of the units seems to influence more in causing the failures.

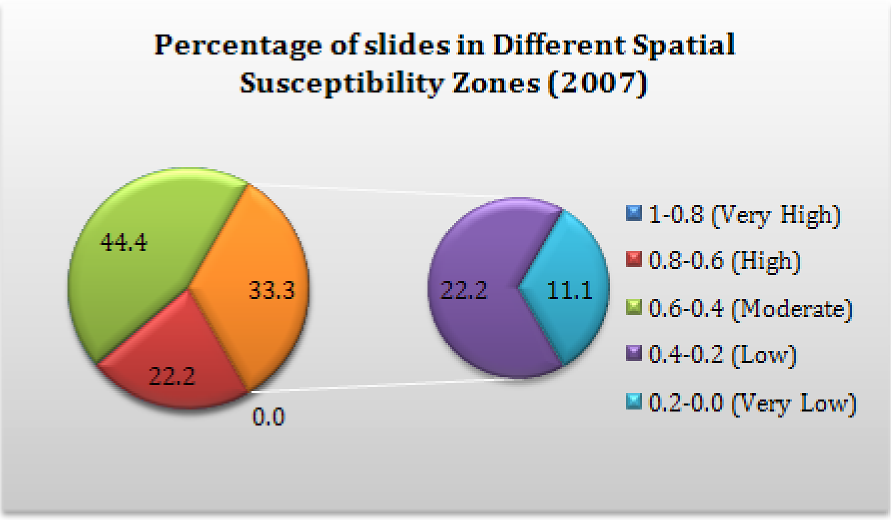


Figure 6.24: Showing percent of landslides in different spatial hazard zones

The relationship between temporal and spatial probability at each failure was again proved that either the failures has taken place in high temporal or in high spatially susceptible units. In most of cases low temporal probability has been compensated by high spatially susceptibility to initiate a failure.

While deriving the spatial probability the old slides that has been identified properly in field, has been taken into account as it was believed that once or twice occurrence in recent past make the parcel of land more susceptible to another failure with little trigger. This assumption was found to match with the reality when it observed that especially in one year scenario most of the old slides has reactivated and failure has taken places in spatially susceptible units.

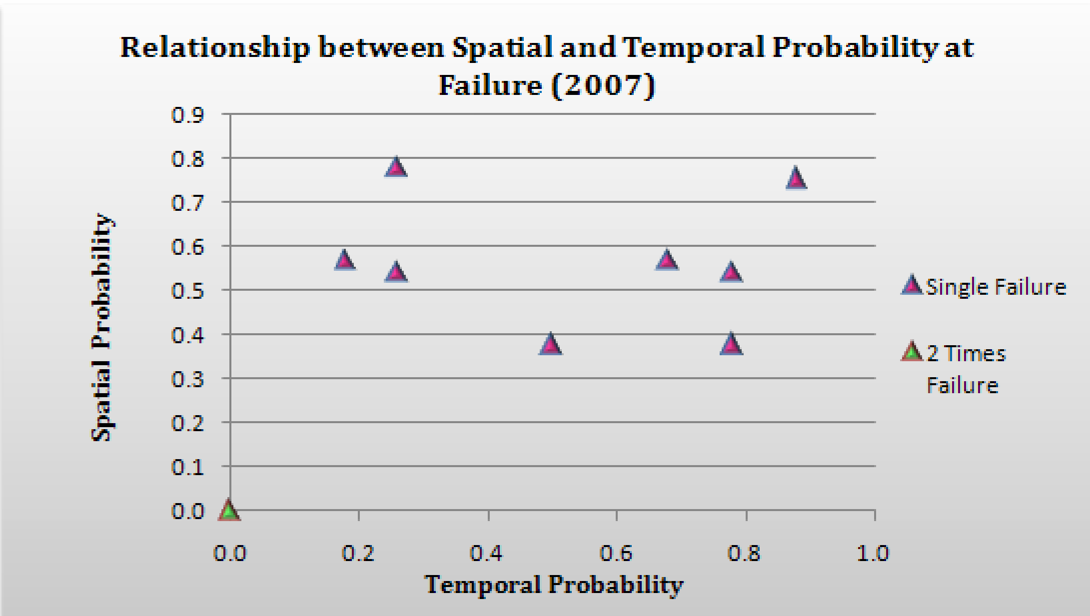


Figure 6.25: Showing relationship between spatial and temporal Probability at Failure

6.6.2.2. Model validation 1 year scenario (2006):

In the year 2006 most of the slides (66%) are found to occur in the low to very low temporal probability units. only 33.3 % of the slope failure events has occurred in moderate to high temporal probability units.

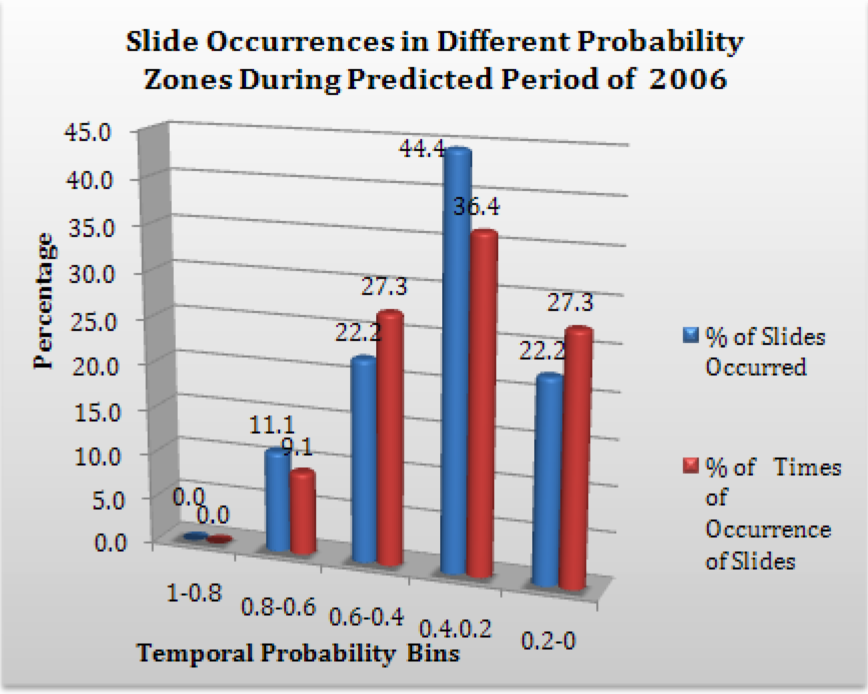


Figure 6.26: Showing percent of landslides in different temporal hazard zones

Results of the spatial validation show an impressive amount of success rate. The 66.6% of the slope failures took place in spatially moderate to very highly susceptible units. Once again through database query it was found that the old failures are reactivated in this year too.

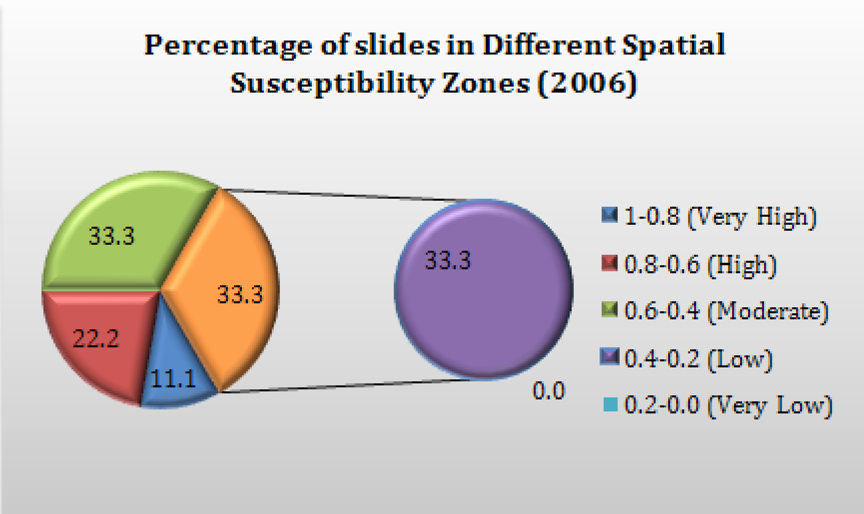


Figure 6.27: Showing percent of landslides in different spatial hazard zones

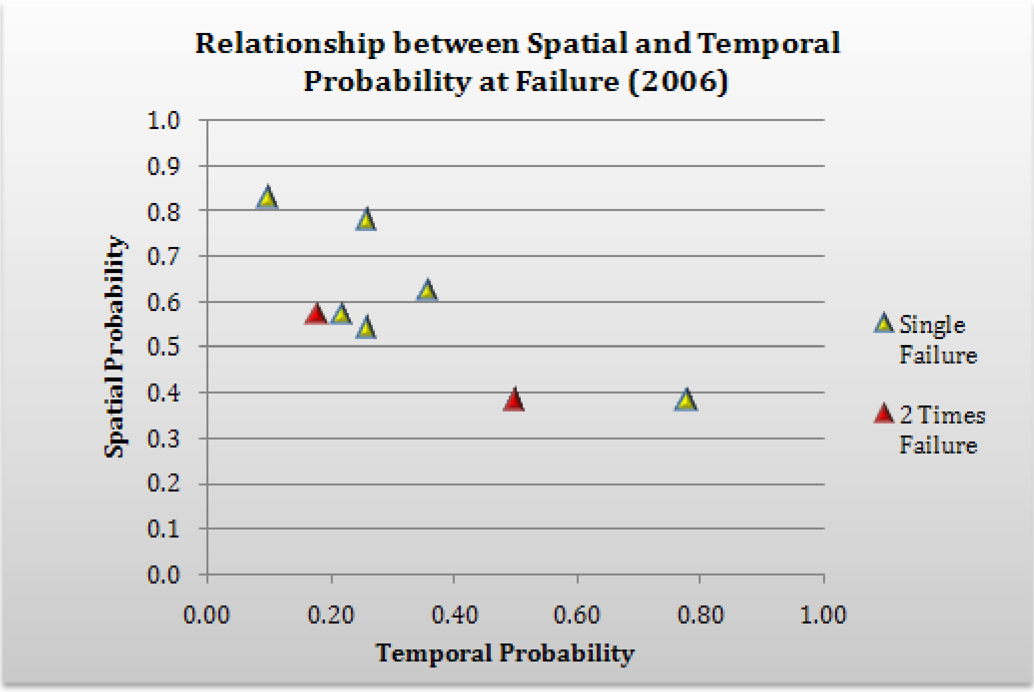


Figure 6.28: Showing relationship between Spatial and temporal Probability

For this year the failures are caused by low temporal and and moderate to high spatial susceptibility. When the spatial susceptibility is low a high exceedance probability has caused the failures.

6.6.2.3. Model validation 1 year scenario (2003):

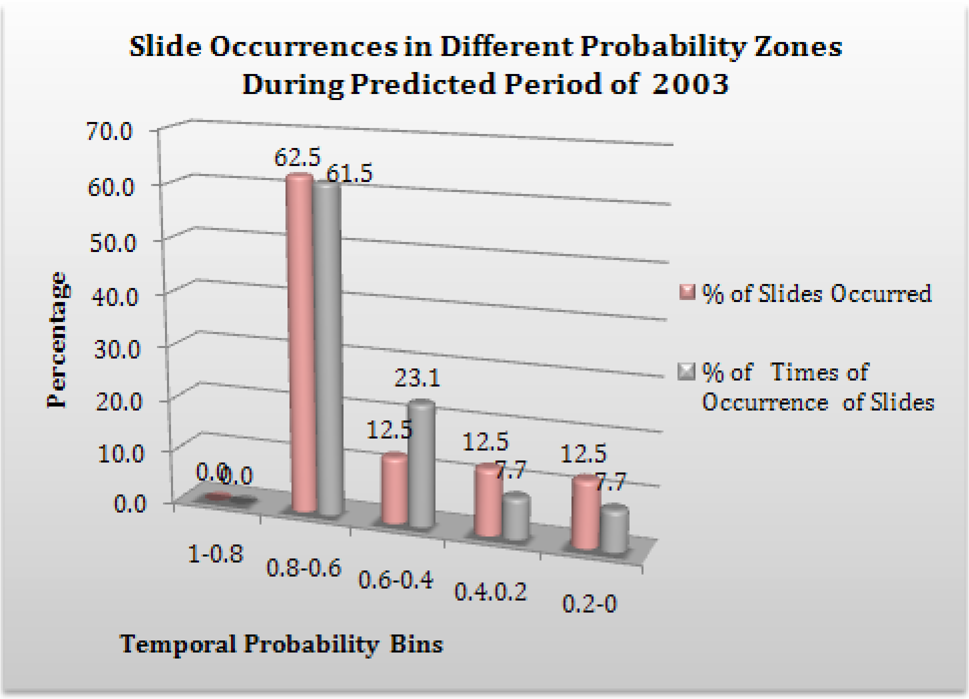


Figure 6.29: Showing percent of landslides in different temporal hazard zones

In the year 2003 the slope failures showed a good agreement with the temporal or the exceedance probability as 75 % of the failures has been observed to take place in moderate to high probability units .where as only 25 % of the failures are observed in low to very low probability units. When the number of times of the events is considered the results are much more impressive as 84.6 % out of total took place in moderate to high temporal probability units.

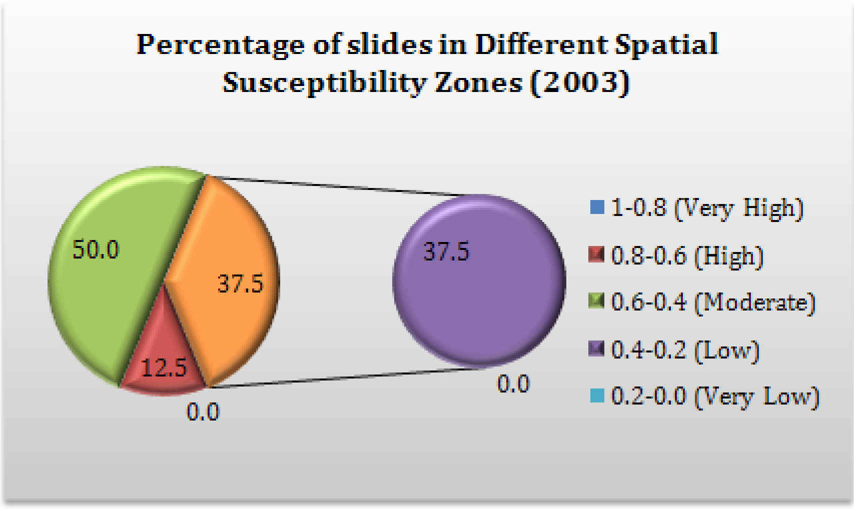


Figure 6.30: Showing percent of landslides in different spatial hazard zones

Similarly around 62.5% of the events happed in moderate to highly susceptible units. And the scatter plot of the two probabilities shows that slope failures are accompanied either with high temporal or with moderate spatial and low temporal probabilities. The number of times the failures occurred is also found to be proportionate with high probability values in both the temporal and spatial domains.

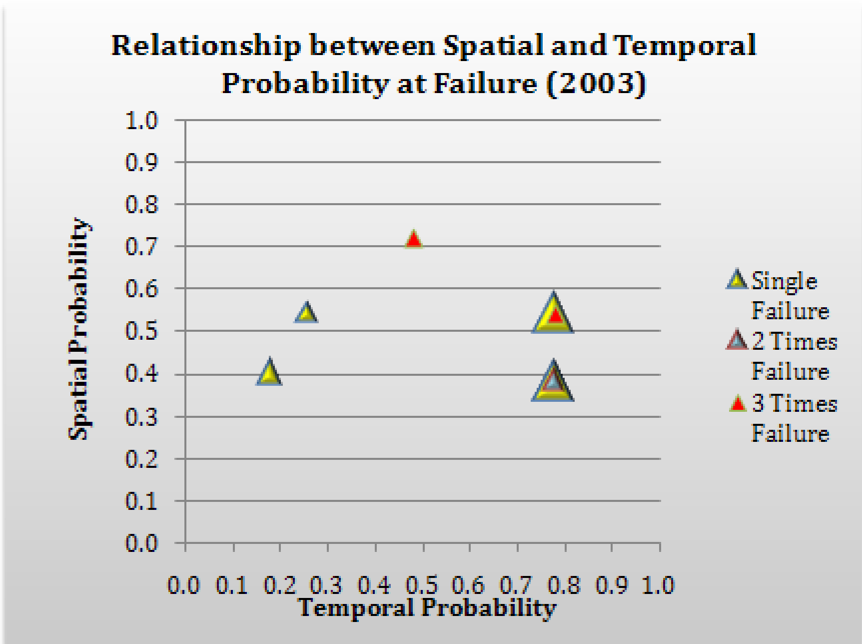


Figure 6.31: Showing relationship between spatial and temporal Probability at Failure

6.7. Frequency Length Analysis:

The slope failures in the road corridor were mainly studied with help of historic records. These records have provided the amount of road length affected by each slide. The document found to be 70 % complete and rest of them are supplemented through field observations and some of them are also derived from satellite image. Thus in the temporal database for slides, the information regarding the road length affected by each slide is is stored in the relational database. It helps to analyze the frequency of various size of landslides occurred in the study area in last 25 years. It can be taken in to consideration that bigger the landslides greater the road length affected which can be assumed as proxy to landslide size from historic records. The frequency magnitude has not been analyzed each mapping unit wise, instead of these the overall trend was observed for the the road corridor. The analysis reveals that the landslides having a length along the road between 20 m to 40 m have occurred in maximum numbers (45 %) followed by slides between a length of 10 to 20 m (37%) where as very small sides and medium to big size slides are very rare events in time.

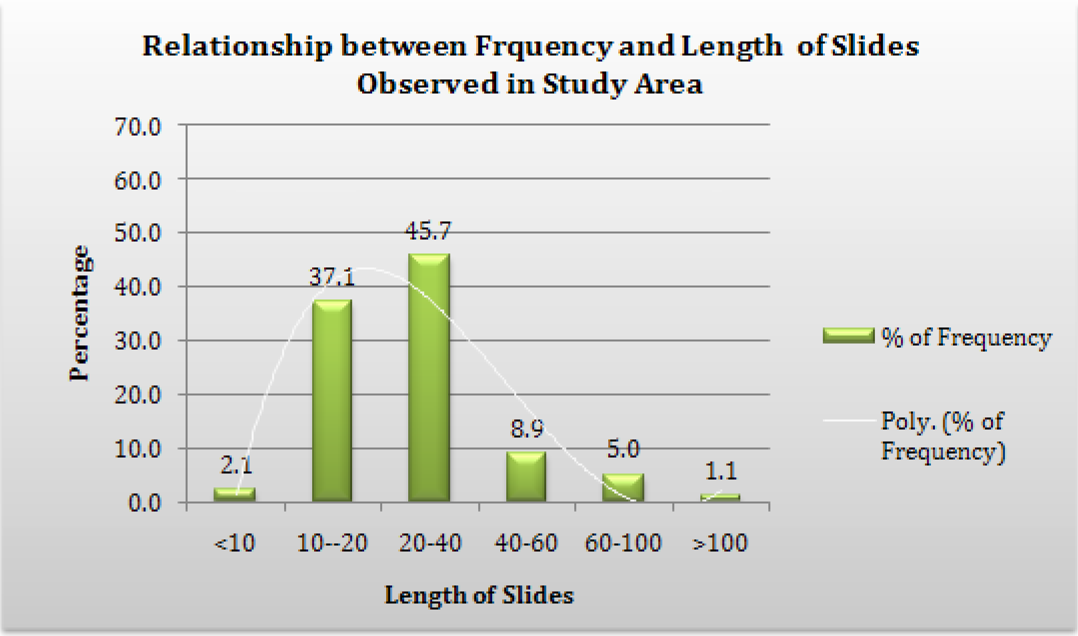


Figure 6.32: Showing the frequency length relationship of landslides in the study area

6.8. Hazard model validation:

The hazard values are derived by simple multiplication of two probability values. The result of these was not satisfactory to the ground truth when correlated. Most of the landslides in the study area are falling in very low to moderate hazard units. According to mathematical rule it can be said that due to multiplication of two hazard values the final values are bound to be reduced when combined. The result of final hazard maps derived for 1 year 5 year and 10 years scenarios are given below which are basically self explanatory.

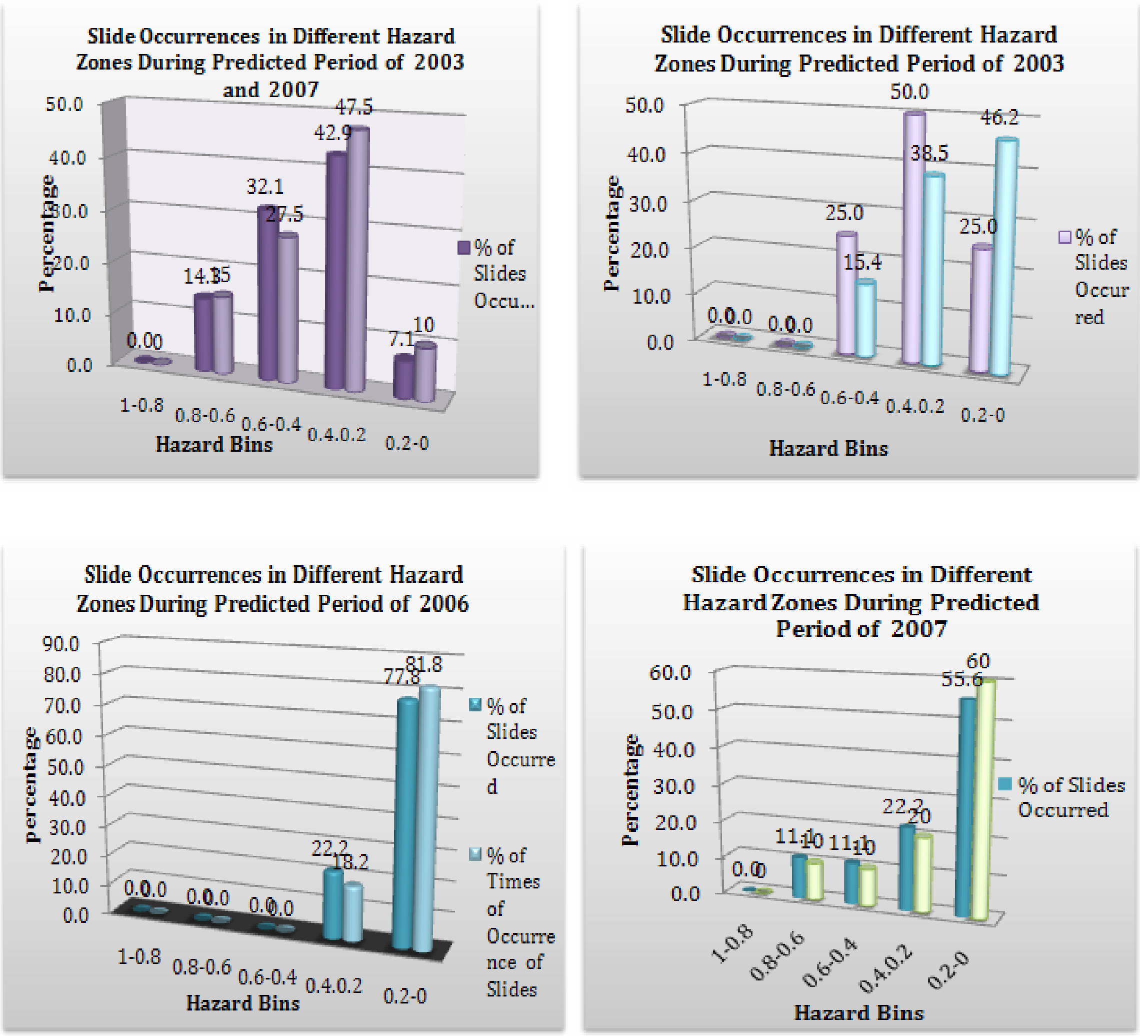


Figure 6.33: showing the hazard percentage of slides occurred in different hazard zones

7. Conclusion and Recomendations:

The chapter presents the conclusions given in the form of answers to the research questions and recommendations provided for future research. The main objective of the research was to derive the temporal probability and the spatial susceptibility of landslide for a rather significant assessment of the hazard scenario based on historical records on (NH 108) in terms of both spatial and temporal point of view for future preparedness and mitigation purposes.

7.1. Conclusions:

In conclusion the answers to the specific research question will be given where it is possible. The major objective of this study was to evaluate the landslide hazard. This is thought to be capable of producing more significant facts regarding the landslide activity of the area. To obtain the overall objective several steps need to be followed which are kept as sub objectives of the study. However the answers to the research questions specific to different objectives of the study are given as follows.

7.2. Objective and Sub-Objective 1:

To develop a methodology for the determination spatial and temporal probability of landslides of a road corridor in the Himalayas based on historical landslide records.

Preparation of a detail temporal landslide inventory of the road corridor of National Highway 108.

Q.1: Is it possible to obtain sufficiently detailed historical landslide information based on registers from the Border Road Organisation?

Preparation of a detailed landslide inventory requires sufficient amount of historic record on landslides. BRO found to be working on the road sector NH 108 for more than 30 years and consistently keeping the records of damages to the road caused by any natural and human induced event. They are also keeping road blockage report along with their reasons described fairly. This include blockage of road due to slides. As landslides are frequently observed in the corridor route the major reason for blockage found to be the slides. Consequently the information on almost all the big and small failures occurred which affected the road was found in the BRO registers DRS Files (Daily Road Stirrup).only problem was some pages were missing for some of the dates. That information was also supplemented with the information contained in other two types of register a) RLS files (Register of landslides) b) HLS files (History of landslides). For 15 kilometer road stretch almost 310 entries of landslide occurrences related to 81 slide locations are found which have affected the road in past 25 years.

Q. 2: What are the historical information required and in what format is to be collected as well as arranged in order to carry out a temporal hazard analysis along the route corridor?

The literatures on temporal landslide hazard assessment and temporal inventory preparation clearly indicates that a temporal landslides database and inventory involves the information on date of occurrence of slides and their exact location on ground. Both the information were successfully derived from the BRO files .The information regarding the landslide date, location and length of road affected by slides are given in typical official code format. Mainly the records are written in format that has been interpreted by decoding the coded information through defence wireless communication network. This decoded information was brought in to a tabulated manner so that the landslide reoccurrences can be calculated from the tabulated records. The length of road affected is also included in the temporal database of the slides which enables the frequency length calculation of slides occurred in last 25 years. The records on volume of the landslides were also available but due to inconsistency it could not be incorporated in assessment of frequency volume relationship. Thus the various sort of historic record of landslides are arranged in tabular as well as relational database format to correlate with spatial information of slides derived.

Q.3: Can the landslides reported by BRO be linked to evidences of past landslides in the field?

Yes the past records of landslides can be successfully linked with evidences in the field. The old slides have been identified with the help of certain man made features (Breast Wall) in completely vegetated portion along the uphill side of the road. And some of the road subsidence's were linked with presence of toe walls on the downhill side of the motor road which were giving support to the retaining walls so that they can be kept intact. The location of the slides are made confirmed with the kilometer stones and the intermediate locations are verified with the meter wheel (provided by the BRO) and all these old slides cannot be marked by it spectral characteristics on the image but as their location and length along the road are recorded and therefore have been mapped with approximation.

Q.4: How many slides in the study area are fresh and reactivated?

In the present study area the slides are grouped in to different classes related to its type and state of activity in the temporal database prepared for the study. Out the total 82 landslides mapped in the area, 19 slides i.e. around 23% of the slides are found in an advancing state. Out of which 5 slide events have taken place in new locations in the year 2007. Apart from that 14 old slides have reactivated during the year 2006 -2007 and also found in an active state. These statistics show the severity of landslide situation in the study area. Another objective behind this classification is mainly evaluating the efficiency of hazard scenarios with current ground situation.

7.3. Sub-Objective 2:

Division of the road corridor into homogeneous geo-environmental mapping units in order to find out temporal probability of sliding of different spatial units.

Q.4: What will be the possible form of homogeneous spatial (mapping) units along the route corridor whose temporal hazard rate will be predicted?

In this case study the slope and the lithology of the road corridor were taken in to consideration for deriving an optimum size of mapping unit along the. As the study is made in GIS environment, based on historic information and the outputs are generated on vector format. Therefore, the size of the mapping unit i.e. the sections of the road length should not be too small to contain a single smallest failure. Consequently considering several factors leading to instability to find out the unique condition units will result in generation of too small units to contain the single smallest failure. This is why one of the major factors to instability i.e. slopes and the lithology is taken in to account to derive the optimum size of the road sections on NH 108.

7.4. Sub-Objective 3:

Development of a methodology for quantitative landslide hazard assessment along a strategic road corridor.

Q.5: How to assess the spatial probability?

The spatial probability of road corridor can be assessed in several ways. The knowledge driven and data driven approaches both consider several factors contributing to instability in assessing the spatial hazard rate but in this study the instead of taking all the parameters contributing to instability the landslide density of both active and old slides are taken into account for deriving the information value for slope failures of road units which is merely an indication of spatial susceptibility of the road units. This is basically the log of ratio of landslide density in each unit and slide density in the total road stretch. These values are stretched between 0 to 1 as the information value of <=0 is considered to be low susceptible to landslides. This is basically based on the assumption that past is the key to present i.e. future landslides can be expected in areas having a large number of past landslides.

Q.6: How to assess the temporal landslide probability?

A statistical data driven approach based on historic landslide information was adapted to assess the temporal probability of occurring one or more landslides. The Poisson model was used for calculating the probability of one or more slides. The Poisson model allows determining the probability of occurrence of any number of landslides but for this study is done for calculating the exccedance probability i.e. the probability of occurrence of one or more landslides. The model produces good results for the hazard rate in 5 years time. But for 1 year scenario the predictions are less successful as compared to the 5 year scenario. This is mainly because of the fact the the mean recurrence interval of slides is greater than 1 year for most of the slides in the study area along with fresh slides are found to take place in new locations due to ongoing anthropogenic activity as well as natural causes like continuous toe removal by the river at several places causing subsidence of the road.

Q.5: How to combine the spatial and temporal probability values in order to derive a quantitative landslide hazard map?

By the definition of landslide hazard it involves the calculation of a joint probability of a mapping unit that can be affected by landslides with a given time and a given local environmental setting. Assuming independence among both the spatial and temporal probabilities a multiplication of the probability factor gives the value of landslide hazard.

The multiplication of temporal and spatial probability values are leading to very low joint probability. In the current case study and the corresponding validation results of the occurrence of slides found to be limited to low hazard values only. For example a high temporal rate of 0.8 when multiplied with low spatial 0.6 produces a 0.48 joint probability. Consequently most of the slides which have occurred in either high temporal or in high spatial probability units are found in low hazard units. Thus the hazard model seems to provide a misleading result when validated with current occurrences.

Q.5: Is there a relation between frequency and magnitude possible?

In this context the the size of the landslides along the road i.e. the length of slides along road is considered and stored in a relational database. Due to ambiguity in the procedural steps, the probability of certain length of slides to hit the road is not been attempted. Where as a simple estimation in terms of percentage which can be perceived as the simple probability of landslides length is estimated for the entire road stretch. Similar results have been found in case of frequency length relationship when compared to frequency volume analysis (Dai and Lee., 200) where the medium to large landslides are found in less number in nature along with the very small sized landslides. In case of the road length the slides between 10- 20 and 20- 40 are found in profusion in the study area. The very small and medium to big sized slides are found as rare events in past 25 years in the investigated area.

7.5. Recommendations:

According to the results of the current study it can be suggested that landslide frequency analysis provides satisfactory hazard prediction with the statistical approach. But the approach requires a huge amount of reliable and consistent data in support of the landslide events of the recent past. Therefore efforts should be made to preserve the data on slide occurrences where existing. In most of the cases in India the organizations like BRO who are keeping the record of slides for past 40 years, generally burn the old files. Thus a huge amount of records of landslides is getting destroyed. Effort should be initiated to preserve the record so that it can facilitate the further research.

On the other hand the research was carried out by assessing the temporal probability of one or more slides while it could have been possible to relate the temporal aspect with rainfall trigger where the rainfall threshold can be estimated and temporal probability of certain number and volume can be derived through estimation of return periods of such rain fall which caused those failures. The rainfall data for a required period cannot be collected which limited the possibility of correlating the temporal aspect with rainfall trigger while it is still remaining as scope of further research.

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