# Chapter 1: Introduction

## 1.1 Background

Landslide is a natural hazard which means the occurrence of a natural condition or phenomenon and acts hazardously in a defined space and time (Varnes 1984; Alcantara-Ayala 2002). It is characterized by the down slope movement of rock, soil, or other debris. Generally, landslides are triggered by heavy rainfall, sudden snowmelt, rapid changes in the groundwater level along a slope, undercutting of the slope by a river especially during a flooding, earthquakes, volcanic eruptions, storm-generated ocean waves and so on.

In natural systems, landslides are recognized as one of the most significant “natural hazards” in many areas throughout the world. Globally, landslides cause billions of dollars in damage and thousands of deaths and injuries each year. Developing countries like Nepal suffer the most, where big amount of the gross national product per year has been lost due to landslides, and 95% of landslide disasters have been recorded in developing countries (Chung *et al.*, 1995). Nepal Government reported that 197 people were killed only in 2007 (Upreti *et al.*, 2008). Worldwide 89.6% of the fatalities were caused by landslides triggered by torrential rainfall. Other triggering processes were construction (mostly undercutting of slopes) (3.4%), mining and quarrying (1.8%) and earthquakes (0.7%), while no cause would be identified for 3.4% of the landslides (Petley, 2008).

There is widespread use of term such as ‘landslide’. However, there is considerable variation between several disciplines and different authors as to the meaning of landslides. Hence, for clarity and consistency, definition of landslide as preferred by the writer and used in this thesis is necessary. In the following sections, reference is made to these key definitions.

Terzaghi (1950) defined ‘landslide’ and ‘creep’ as follows: “a landslide is a rapid displacement of a mass of rock, residual soil, or sediments adjoining a slope, in which the centre of gravity of the moving mass of rock, residual soil, or sediments adjoining a slope, in which the centre of gravity of the moving mass advances in a downward and outward direction. A similar movement proceeding at an imperceptible rate is called creep”.

The definition of the term ‘landslide’ was again revised, by Varnes (1984), as follows; “the term landslide comprises almost all varieties of mass movements on slopes, including some, such as rockfalls, topples, and debris flows, that involve little or no sliding.

Landslide Hazard maps describe an unstable condition arising from the presence or likely future occurrence of slope failure. There are two general types of landslide hazard maps each of which provides different level of information and detail:

- Landslide Susceptibility Maps describe the relative likelihood of future land sliding based solely on the intrinsic properties of a locale or site. Prior failure (from landslide inventory), rock or soil strength and steepness of slope are three site factors that most determine susceptibility.
- Landslide potential maps describe the likelihood of land sliding (susceptibility) jointly with the occurrence of triggering event (opportunity). Potential commonly based on three factors determining susceptibility plus an estimate or measure of the probability (likelihood of occurrence) of a triggering event such as earthquake or excessive rainfall.

Landslide hazard mapping helps in reduction of landslide disaster by assessing the risks and taking appropriate actions. Landslide hazard maps help planners, decision makers to select suitable locations for sitting development scheme, such as building and road, construction of bridges, hydroelectric projects, flood control structures and irrigation canals etc in mountainous areas. Landslide hazard maps identify and delineate the unstable hazard prone area. So environment regeneration program can be initiated adopting suitable irrigation measures within the watersheds.

Similarly hazard mapping may enable for prioritization of the limited resources to areas where landslides problems are existed. It may be useful as the basis for planning future development scheme.

## 1.2 Statement of Problem

Landslide events are common phenomena and impacts are so severe. Also frequency of landslide is in increasing trend in recent years. Poudel (2001) concluded that in Nepal during the period 1971-2001, 70.3% were occurred only in 1991-2001 decade. Hence the understanding of cause process and landslide hazard zonation on watershed is important for reducing the risk of landslide hazard and environment protection.

Kulekhani watershed area of the Makwanpur district of Central Development Region is one of the densely populated areas which have been one of the worst disaster hit areas in Nepal. The devastating floods, landslides and debris flow events of July 1993 were in fact, the most severe in the history of flood and landslides disaster in Nepal. Unprecedented high intensity precipitation occurred in the upper parts of the Makwanpur and Dhading districts from July 19 to 21, 1993. The volume of the precipitation within 24 hours ranged from 362 mm at Nibuwatar to 320 mm at the Kulekhani Dam site, and a maximum of 539.5 mm at Tistung. As a result, the Kulekhani Reservoir received about 4 million cubic metres of sediments.

The siltation survey carried out by the Department of Soil Conservation in 1994 in the Kulekhani reservoir indicated that the sediment deposited during the 1993 monsoon was about 771 hectare meter. During that period, the gross capacity of the reservoir was reduced by 10.19 million cubic meters of its capacity at construction, of which 7.71 million cubic meters of sediment were due to 1993 floods (Dhital and Upreti, 1996). Although several studies have been done, but this study partly fulfill the knowledge gap in regard to landslide hazard zonation mapping of the study area, thereby helping the planner and administrator to search for the safer place to develop the infrastructure needed for the development. Also the imminent danger of losing Kulekhani reservoir can also be addressed.

In light of abovementioned problem, the relevant research questions are:

- What are the major causes of landslide?
- What is the relation between a dependant variable (landslide) with other independent variables (slope, aspect, relief, internal relief, river distance, landuse)?
- How much of the areas of watershed is hazard prone?

- Is there a major difference between various Bivariate Statistical Analysis methods in predicting the hazard areas?

### 1.3 Research Objective:

#### 1.3.1 General Objective:

- To prepare landslide hazard map to assess the spatial landslide susceptibility of Kulekhani Watershed

#### 1.3.2 Specific Objectives:

- To study and prepare parameters maps influencing the occurrence of landslide
- To prepare landslide hazard map of the study area by different Bivariate Statistical Analysis Method
    - ✓ Probability Method or Frequency Ratio Method
    - ✓ Statistical Index Method
    - ✓ Landslide Susceptibility Analysis
    - ✓ Weight of Evidence Modelling
    - ✓ Certainty Factor

Hence, final goal of this study is to produce landslide susceptibility map in order to inform local administrators and local inhabitants about the possibilities of landslide occurrence in future. In this way, the result of this thesis may contribute to the remedy of the landslide hazard and damages in the future.

### 1.4 Justification/Rationale of the study

The occurrence of natural hazards is a serious constraint for economic development, particularly in developing countries, where the economic loss due to the impact of natural hazards after makes the difference between economic growth and stagnation.

Kulekhani watershed lies in the Lesser Himalaya in Makawanpur district in Central Nepal. This region of the Himalayan belt in Nepal is highly populated and most prone to landslide. The area is home to the only storage type powerhouse in Nepal and supports approximately one sixth of total electricity generation in Nepal. During the landslide/debris-flow disaster in July 1993, the reservoir received tremendous amount of sediments i.e. almost thirty times the average annual sediments. More than 1500 people were killed in the Kulekhani watershed and neighbouring areas (JICA, 1997). This wrecked havoc on the infrastructure of the Kulekhani dam.

Dhakal *et al.*,(2000) has used Quantitative Scaling type II (Discriminant) Analysis for producing hazard map of the Kulekhani watershed. But since, they applied only one method to predict and prepare landslide hazard map, high reliability may not be ascertained. So based on different literature and studies in an around the study area, a well set hazard map by employing different methods is still lacking. This dissertation would help in plugging the loopholes and will generate the hazard maps that would be helpful in overall sustainable development of the study area which has quite a significant history in the annals of Nepal.

## 1.5 Limitation of the Study

The present study studies the effect of seven major landslides causes viz. slope, aspect, relief, internal relief, river distance and landuse and geology. This relation is used as a basis of hazard zonation map. Apart from these, soil, ground water depth, drainage density plays a considerable role in causing landslide have not been considered in this study. Also, the study basically depends on the map data obtained from various sources; there might be some error in truly depicting the study area. The digital data such as geological map, landuse map, landside inventory map are obtained from Department of Mines and Geology and Survey department. These data cannot be generated by this researcher for accomplishing the above mentioned objective, so, for the dissertation relying on their prepared map is the only option. Also the contour interval of 20m is slightly more which may not give accurate prediction. So, there might not be accurate map in predicting the hazard area.

# Chapter 2: Literature Review

## 2.1 General Concept of Landslide

Landslide is one of the many natural processes that shape the surface of the earth. Only when they do threaten the survival of mankind they represent the hazard. Landslide belongs to much broader group of slope processes referred to as mass movement. The definition of mass movement includes all those processes that involve the outward and downward movement of slope forming materials under the influence of gravity. Some mass movement process such as soil creep, are almost imperceptibly slow and diffuse while other, such as landslide, are capable of moving at high velocity, discrete and have clearly identifiable boundaries, often in form of shear surfaces (Crozier, 1986). Landslides are manifestation of slope instability. In particular, it identifies those aspects of landslides that make them hazardous and analysis the vulnerability at risk in the face of landslide activity.

## 2.2 Landslide influencing factors

Factors influencing where landslides occur can be divided into two sets, permanent and variable (Sharpe, 1938). Permanent factors are characteristics of the landscape which remain unchanged or very little from a human perspective. The steepness of a slope or the type of rock, for example, presents changes only with the passage of long periods of time. Permanent factors such as rock type and slope steepness can be recognized and identified for specific landslides long after their occurrence (DeGraff, 1978). By examining existing landslides in an area, it is possible to recognize how permanent factors contributed to these slope failures. Identifying conditions and processes promoting past instability makes it possible to use these factors to estimate future landslides (Varnes, 1984).

Variable factors are landscape characteristics that change quickly as a result of some triggering event. Ground vibration due to earthquakes, a rapid rise in groundwater levels, and increased soil moisture due to intense precipitation are examples of variable factors. It is often necessary to be present at the time a landslide occurs or shortly thereafter to assess these factors. Due to the lack of long-term records relating landslide activity to historic earthquakes, storms, or other initiating factors, permanent factors are usually used to estimate landslide hazard. As such, identifying landslide areas is not an accurate science and leads, in general, to depicting hazard-prone areas based on estimation. At best, landslide and landslide susceptible areas can be identified along with expected triggering events. At worst, some areas may not be detected at all.

Varnes (1984) explained there are many factors that should be considered to analyze landslide hazard. Soeters and Westen (1996) divided those factors into five groups as described as follow.

- Geomorphology factors such as data of terrain unit, geomorphological sub-unit, types of landslides
- Topography factors such as data of digital terrain model, slope direction and length, concavities
- Engineering geology factors such as data of lithology, material sequences, structure of geology, and seismic acceleration
- Landuse factors such as data of infrastructure development (recent and older) and landuse map (recent and older)
- Hydrology factors such as data of drainage, catchment area, rainfall, temperature, evaporation and water table map

As mentioned by Soeters and Westen (1996), it may not be necessary to include all parameters; because it depends which ones are relevant for the study area. It also provides optimum results to evaluate landslide hazard by using few parameters.

### 2.2.1 Geological Factors

According to the Sidle and Ochiai (2006), there exists a relationship between slope instabilities and different types of regolith material. But, the relationship is largely depending upon the type of regolith material. Examples of a strong relationship between landslide and different types of regolith material were given by researcher (Wakatsuki *et al.,* 2005). Weathering and unstable bedding sequences are also important geological factors for landslide hazards.

#### 2.2.1.1 Soil Engineering, Chemical and Mineralogical Factors

Engineering, chemical and mineralogical properties of soil are strongly related to the mechanical behavior of soils and their equilibrium. Soil shear strength is a fundamental property that governs the stability of natural and constructed hillslopes. It is not a unique value, but is strongly influenced by loading, unloading, and especially by water content (Long, 2008). The shear strength is basically described as a function of normal stress on the slip surface (σ), cohesion (c) and internal angle of friction (φ). The relationship of these properties to other characteristics of natural soil has been given by Terzaghi and Peck (1967).

Clay minerals are the most important chemical weathering product of soil and regolith. Many researchers have attempted to link specific clay minerals to landslide hazard and slide type (Yatsu, 1966).

#### 2.2.1.2 Geomorphic Factors

Geomorphic factors such as Slope Gradient, Slope shape, Slope Aspect, Altitude, and etc. have significant role for landsliding and considered as the major factors for landslide hazard (Pachauri and Pant, 1992; Dai and Lee, 2002).

#### 2.2.1.3 Hydrologic Factors

Hydrology plays an important role for landsliding. Some of the most significant hydrologic processes in this respect are intense precipitation, water recharge into soil, lateral and vertical movement within the regolith, evapo-transpiration and interception.

#### 2.2.1.4 Seismicity

Seismicity is one of the major factors for devastating landslides. The most abundant types of earthquake-induced landslides are rock falls and slides of rock fragments that form on steep slopes. However, almost every other type of landslide is possible, including highly disaggregated and fast-moving falls, more coherent and slower-moving slumps, block slides, and earth slides, and lateral spreads and flows that involve partly to completely liquefied material (Keefer, 2002). Liquefaction is special type of landslide that is typical for earthquakes which can cause fissuring or subsidence of the ground. It can have devastating effects during large earthquakes. Similarly, some of the largest and most destructive landslides have been associated with volcanoes. These can occur either in association with the eruption of the volcano itself, or as a result of mobilization of the very weak deposits that are formed as a consequence of volcanic activity.

### 2.2.2 Man-Made Factors

The direct and indirect activities of people resulted many landslides. But any attempt to address all activities by people that induce landslide occurrences will be incomplete. Therefore, only some examples will be given as.

- Undercutting during construction of highways and railroads increases the average slope gradients, and increases the chance of slope failures.
- Overloading of hillslope by housing construction is common. This extra weight may increase the chance of slope failure; altering the hydrology may have dramatic effects on hillslope stability.
- Clear cutting of trees promotes soil erosion and weakens the support of soils by tree roots. It also reduces evapo-transpiration and raises the water tables.
- Vibrations occurring in earthquake consequence by hydroelectricity lakes, or other artificial causes (machine activities, underground explosions).

## 2.3 Types of Landslides

### 2.3.1 Landslide Classification Systems

Slope movements have been classified in many ways since long with each method having some particular usefulness or applicability related to the recognition, avoidance, control, or correlation of the hazard. The classification of a landslide based on its activity is particularly relevant in the evaluation of future events. The recommendations of the Working Party on World Landslide Inventory (1993) define the concept of activity with reference to the spatial and temporal conditions, defining the state, the distribution and the style. In this concept, the first term describes the information regarding the time when the movement took place, permitting information to be available on future evolutions, the second term describes, in a general way, where the landslide is moving, and the third term indicates how it is moving.

The most widely used classification scheme developed by Varnes (1978) divides landslides into different types according to the material and the type of movement (Varnes 1978; Cruden and Varnes 1996). This classification distinguishes five types of mass movement plus combinations of these principal types along with types of material (Table 2.1).

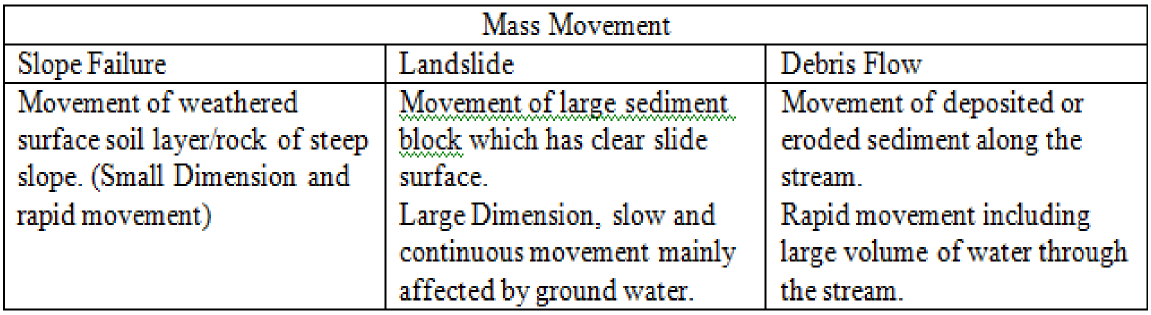
Table 2.1 Schematic Landslide Classification (Adopting the classification of Varnes 1978 and taking into account the modifications made by Cruden and Varnes, in 1996).

| Type of movement | | | Type of material | | |
|---|---|---|---|---|---|
| | | | Bedrock | Engineering soils | |
| | | | | Predominantly fine | Predominantly coarse |
| Falls | | | Rock fall | Earth fall | Debris fall |
| Topples | | | Rock topple | Earth topple | Debris topple |
| Slides | Rotational | | Rock slump | Earth slump | Debris slump |
| | Translational | Few units | Rock block slide | Earth block slide | Debris block slide |
| | | Many units | Rock slide | Earth slide | Debris slide |
| Lateral spreads | | | Rock spread | Earth spread | Debris spread |
| Flows | | | Rock flow | Earth flow | Debris flow |
| | | | Rock avalanche | | Debris avalanche |
| | | | (Deep creep) | (Soil creep) | |
| Complex and compound | | | Combination in time and/or space of two or more principal types of movement | | |

Rock, earth and debris are the terms generally used to distinguish the materials involved in the landslide process. For example, the distinction between earth and debris is usually made by comparing the percentage of coarse grain size fractions. If the weight of the particles with a diameter greater than 2 mm is less than 20%, the material will be defined as earth; in the opposite case, it is debris. Speed of movement and amount of water mixed with the material are secondary parameters defining some landslide types. Recognizing the types of landslides in an area helps to explain how and where factors have contributed to slope instability in the past.

According to Preventive Classification (JICA), the following table 2.2 shows the different types of mass movement. This classification is based on type, speed, dimension of movement and spatial composition.

Table 2.2 Illustration of Landslide Classification

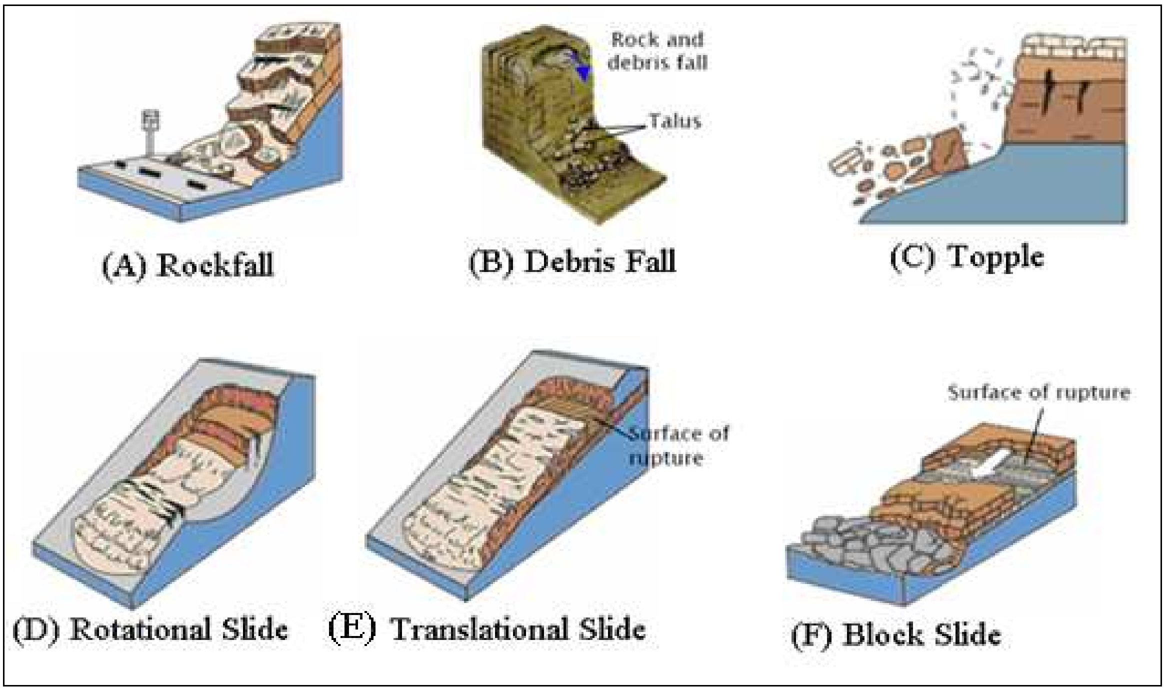


| Mass Movement | | |
|---|---|---|
| Slope Failure | Landslide | Debris Flow |
| Movement of weathered surface soil layer/rock of steep slope. (Small Dimension and rapid movement) | Movement of large sediment block which has clear slide surface.<br>Large Dimension, slow and continuous movement mainly affected by ground water. | Movement of deposited or eroded sediment along the stream.<br>Rapid movement including large volume of water through the stream. |

Source: Department of Water Induced Disaster Prevention (1999)

### 2.3.2 Landslide Types

Different landslide types can be identified as shown in Figure 2.1 (USGS, 2004). These are considered as fall, topples, slides (rotational slides, translational slides), slumps, lateral spreads, flows (rock flows, debris flow, debris avalanches, earth flow, mud flows) and Creep. Complex movement is a combination of falls, topples, slides, spreads and flows.



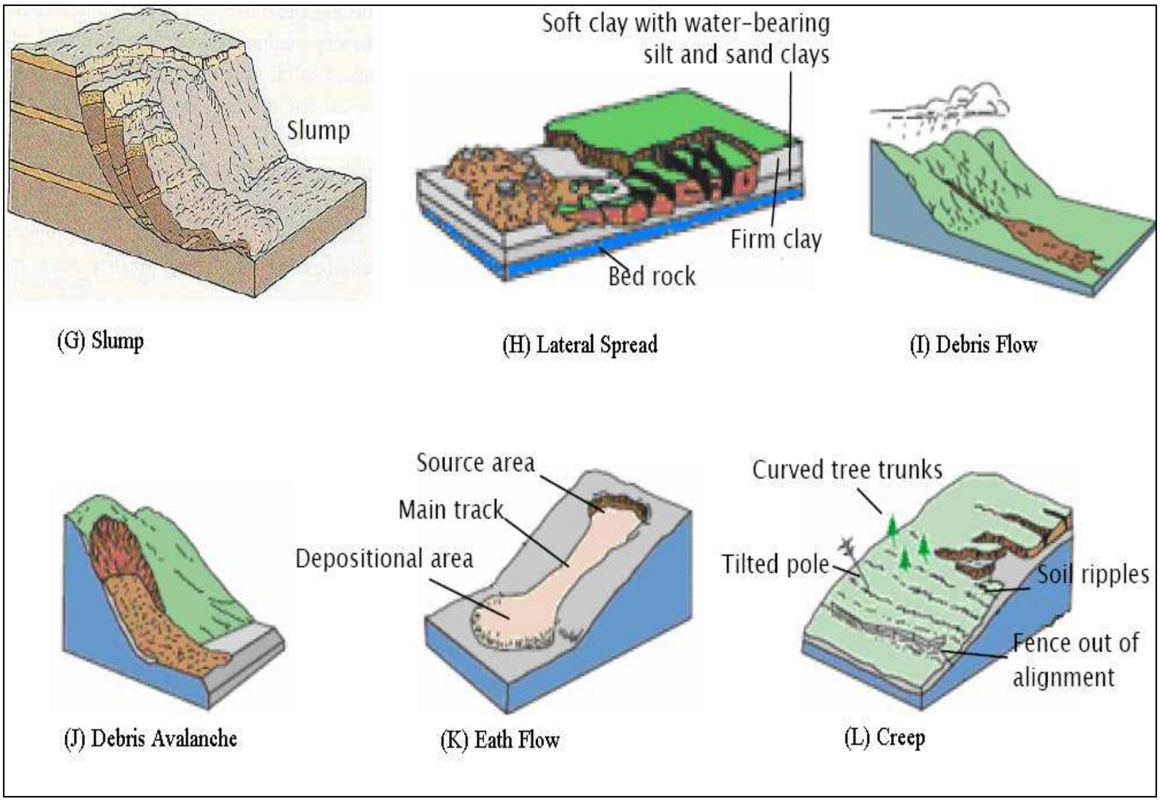


Figure 2.1 Schematic illustrations of the major types of landslide movement (USGS, 2004)

## 2.4 Landslide Mapping

To determine existing landslide hazard and undertake an estimation of future landslide occurrence, an understanding of the conditions and processes controlling landslides is required. A map of existing landslides serves as the basic data resource for understanding these conditions and processes. Existing landslides and their relationship with three other key factors on the basis of a hazard assessment are bedrock, slope steepness, and hydrology.

### 2.4.1 Landslide Inventory Mapping

A landslide inventory map identifies the definite and probable areas of existing landslides, and is the most basic requirement for a landslide hazard assessment. The product of a landslide inventory map is a spatial distribution of landslides as points or to scale. Landslide inventory maps can and often are used as a basis for other landslide hazard zonation techniques or for an elementary form of a hazard map. A typical landslide inventory map is based on aerial photograph interpretation, ground survey, and/or a database of historical movements within the area. These maps, however, only provide information for a short period of time, and they provide no insight into temporal changes in landslide distribution.

In landslide hazard assessment, the historic information on landslide occurrences is by far the most important, as this gives insight into the frequency of the phenomena, the types involved, the volumes and the damage that has been caused. Landslide inventory maps, derived from historic archives, field data collection, interviews and image interpretation are essential but unfortunately often lacking (Van Westen *et al.,* 2006).

Despite the fact that the quality of historical evidence is strongly dependent on recording procedures and available records, this approach provides an indication of at least the minimum level of landslide activity in an area. The issue of using historical data in natural hazard assessments is discussed by Guzzetti *et al.* (1994).

Generally, widely used methods for making a landslide inventory map are field investigations and remote sensing techniques. By fieldwork surveys, evidence of current and former landsliding can be determined from slope morphology, sedimentary deposits, or impact features (e.g. deformed trees). As this type of evidence deteriorates or is obliterated progressively with time, care has to be taken in establishing long-term trends in occurrence. A wide range of both relative and absolute methods has been employed for dating of field evidence (Lang *et al.,* 1999).

Remote sensing techniques greatly aid in the investigation of landslides, on both local and regional scale. Although these cannot replace fieldwork, for interdisciplinary research strategies and testing of reliability of landslide prediction models, remote sensing techniques do offer an additional tool from which we can extract information about landslide causes and occurrences. The landslide information extracted from remotely sensed products is mainly related to morphology, vegetation and hydrologic conditions of a slope. Especially, stereo-remote sensing products reveal the true morphodynamical features of landslides. Other remote sensing data for landslide inventory mapping are: LANDSAT (Honda *et al.,* 2002), SPOT (Yamaguchi *et al.,* 2003), IRS-1 (Nagarajan *et al.,* 1998), ASTER's 14 multi-spectral bands, IKONOS or Quickbird (Petley *et al.,* 2002).

Photo-grammetrical methods using aerial photos are very useful for identification of landslides. Such methods have now become standard procedures that can be carried out by most landslide research groups. Moreover, comparing aerial photographs of an area can give an indication of the frequency and extent of landslide events. When using photographs it is important to use photographs from different periods, as often land development can display the presence of landslide features. Looking at the different periods, landslide causes can be detected and evaluated. Chandler and Brunsden (1995) gave excellent applications of aerial photo-grammetry for landslide detection.

### 2.4.2 Landslide Hazard Mapping

The landslide hazard map indicates the probability of landslides occurring throughout an area. A perfect landslide hazard map shows not only the chances that a landslide may form at a particular place, but also the chances that a landslide from farther upslope may strike that place (National Research Council, 2004). The "landslide hazard zonation" is the division of the land surface into homogenous areas and the ranking of these areas according to their degrees of actual or potential natural hazards from landslides or other mass movements on slopes (Varnes, 1984).

Determining the spatial and temporal extent of landslide hazard requires identifying those areas which are, or could be, affected by a landslide and assessing the probability of such landslides occurring within a specified period of time. Specifying a precise time frame for the future occurrence of a landslide can be difficult. As a result, landslide hazard has often been represented by landslide susceptibility, where only the predisposing and preparatory landslide causes are described. Landslide susceptibility is defined as a function of the degree of the inherent stability of the slope together with the presence and activity of causative factors capable of reducing the excess strength and ultimately triggering movement (Crozier and Glade, 2005). The identification of causative factors is the basis of many methods of susceptibility assessment. The factors may be dynamic (e.g. pore water pressure), or passive (e.g. rock structure) and may also be considered in terms of the roles they perform in destabilizing a slope (Crozier, 1986). In this sense, the factors can be pre-conditioning factors (e.g. slope steepness), preparatory factors (e.g. deforestation) or triggering factors (e.g. seismic shaking).

### 2.4.3 Landslide Hazard Zonation

#### 2.4.3.1 Principles

Despite different ideas among researches, all proposed methods for slope instability studies are based upon some widely accepted principles or assumptions (Varnes 1984; Turner and Schuster 1996; Guzzetti *et. al,* 2005,). They are as follows.

- The main conditions that cause landslides can be identified, and most can be mapped. In fact, slope failures leave distinct features that can be recognized, classified and mapped in the field or through remote sensing, chiefly stereoscopic aerial photographs (Varnes 1978; Cruden and Varnes 1996).
- For landslides, “the past and present are keys to the future” (Varnes 1984; Carrara et al., 1991). Under this assumption, landslides in the future are likely to occur under the same geologic, geomorphic and hydrologic conditions as those that led to

landslides in the past. Hence, the understanding of past failures is essential in the assessment of landslide hazard.

- The conditions that lead to landslides can be used to determine the likelihood of future landslide occurrence. The conditions can be varied and related in different ways. However, if the processes involved can be understood, then extrapolation from point/site information is possible to wider regions. Crozier (1986) confirmed that conditions which cause landslides (instability factors), or are directly or indirectly linked to slope failures, can be collected and used to build predictive models of landslide occurrence, because landslides are controlled by mechanical laws that can be determined empirically, statistically or in deterministic fashion.
- Landslide occurrence, in space or time, can be inferred from heuristic investigations, computed through the analysis of environmental information or inferred from physical models. Therefore, an area can be zoned into susceptibility classes ranked according to different probabilities (Carrara *et al.,* 1995; Soeters and Van Westen, 1996; Aleotti and Chowdhury).

Ideally, evaluation of landslide hazard and its mapping should be derived from all of these assumptions. Failure to comply with them will limit the applicability of any susceptibility assessment, regardless of the methodology used for the investigation.

## 2.5 GIS Modeling Methods

Geographic Information System (GIS) is a set of powerful tools for collecting, storing, retrieving, transforming, analyzing and displaying spatial data from the real world for a particular set of purposes (Burrough, 1986). GIS provides strong functions both in geo-statistical analysis and database processing. In addition, the extension of the analysis to include environmental impact assessment of a slope failure can be easily and effectively performed using GIS. Therefore, GIS methods for modeling slope instability have been employed by different investigators throughout the world. Varnes (1984), Van Westen (1994), Soeters and Van Westen (1996), Aleotti and Chowdhury (1999), Dahal *et al.,* (2008), Yalcin (2008), Das *et al.*, (2010), Regmi *et al.*, (2010).

Literature review of the landslide hazard reveals that methods for ranking slope instability factors and assigning different hazard levels can be divided into (1) qualitative or quantitative, and (2) direct or indirect.

The qualitative approach is completely based on field observations and a prior knowledge of the expert. In this approach, an expert uses geomorphological and topographical maps to identify landslides and makes assumptions about those sites where movement has occurred and is likely to occur again. In this way, the expert develops decision rules or assigns weighted values to geomorphological and topographical factors and overlays them to develop a hazard map.

The quantitative approach is based partly on field observation and knowledge of the expert and partly on statistical computation of the weight of probabilities of occurrence of a landslide for factors that causes landslides. In this method, weight value are data driven and are normally expressed in the form of a favorability function in bivariate statistical analysis (Dahal *et al.,* 2008, Regmi *et al.,* 2010) and regression function in multivariate statistical analysis (Atkinson and Massari 1998; Das *et al.,* 2010). This approach uses statistical and/or map algebra to assess the role of various factors that cause landslides. Therefore, it produces numerical estimates, i.e. probabilities of the occurrence of landslide phenomena in any susceptibility zone (Guzzetti *et al.,* 2005, Devkota 2010).

The most common approaches proposed in the literature can be grouped into five main categories (Carrara *et al.,* 1992 , Van Westen 1993; Soeters and Van Westen 1996; Aleotti and Chowdhury 1999; Guzzetti *et al.,* 1999; Committee on the Review of the National Landslide Hazards Mitigation Strategy 2004), namely (1) direct geomorphological mapping; (2) analysis of landslide inventories; (3) heuristic or index based methods; (4) statistical methods, including neural networks, fuzzy logic and expert systems; and (5) process based conceptual models (Table 2.3).

Table 2.3 Characteristics of Landslide Susceptibility Methods (Van Westen *et al.*, 1997a)

| | Direct | Indirect | Qualitative | Quantitative |
|---|---|---|---|---|
| Geomorphological Mapping | ✓ | | ✓ | |
| Qualitative Method | | ✓ | | |
| Analysis of Inventories | | ✓ | | ✓ |
| Quantitative Method | | ✓ | | ✓ |
| Process Based Method | | ✓ | | ✓ |

## 2.6 Review of Previous works

A number of geological investigations are being carried since 1875 in the Central Nepal at regional and local scale. The brief description of the geological works is given below. Medlicott (1875) took a traverse from Amlekhgunj through Kathmandu to Nuwakot. He was the first to discover the Chandragiri-Phulchowki fossiliferrous beds. He described the sedimentary and the low grade metamorphic rocks to the south and gneiss and the high grade rocks to the north of Kathmandu.

Auden (1935) carried the first systematic geological investigation in Nepal, who visited some parts of the Eastern and the Central Nepal. He gave a fairly good account of the geology of this part of the Himalaya. He studied the fossils from limestone of Chandragiri and assigned the Ordovician age to these rocks. He noticed superposition of the high grade metamorphic rocks over the low grade metamorphic rocks in the Mahabharat range.

Gansser (1964) compiled the geology of Nepal and tried to reconstruct the comprehensive and total geological configuration of the Himalaya. In his work, he has tried to give a regional tectonic outline of the whole Himalaya including Nepal. Hagen (1969) worked the first most important and extensive study on the Nepal Himalaya. He developed the concept of nappe structures in the Nepal Himalaya. He divided the geology of the study area into two Nappes, the Kathmandu Nappe and the Nuwakot Nappe. The distinction of these was based on conspicuous differences in composition, metamorphic grade and age.

Stöcklin and Bhattarai (1977) studied the geology of the Kathmandu area and Mahabharat range based mainly on the photo-geological interpretations supported by field works. They developed the stratigraphy of the Central Nepal. Apart from the tertiary Siwalik and Quaternary deposits, they grouped the rocks into two largest units, Nuwakot Complex and Kathmandu Complex. These complexes are further sub-divided into formations and members.

Laban (1979) presented the finding of a study of the occurrence of landslide in Nepal based on landslide counts from aircraft. After reconnaissance over flight, it provided quantitative data on natural and total density of landslide in Nepal by ecological regions. As well as associated with stream or river and with roads or trials. He concluded that 72 percent landslides were natural and 28 percent were due to man's activity. Landslide density ranged from 0.2 to 2.8/km$^2$.

Based on the land system, Department of Soil Conservation and Watershed Management has presented the districts' watershed condition of Nepal. It has stated that 25 districts have good watershed condition, 25 districts have fairly good condition, 13 districts have marginal condition, 5 districts have poor condition and 7 districts' watershed condition is very poor. The watershed condition of the Makwanpur district is fairly good.

Dikshit (1983) studied the landslide present in Nepal more than decades, high moisture contnt, steep slope; he considered deforestation and agricultural activities with irrigation in steep slope as main causes of landslides.

Caine and Mool (1987) studied the landslide in Kathmandu-Kakani area as part of the United Nation University hazard mapping project. They explained that the main factors contributing to the development of landslides are lithology, high relief, seasonally high water tables and deforestation. They pointed that slope morphometry and slope materials are importance controlling factor of landslide the study area. They found that the estimated rate of surface lowering by landslide is 12mm per year.

Gurung and Khanal (1987) have studied the landscape process in the Churia range of Central Nepal they identified various geomorphic processes and prepared geomorphic mass of the Churia range with using aerial photographs and verified by field work. They found that about 40-60% landslide were located within half and mile distance along some riverbanks. They also found that the forestland was being replaced by agriculture land even up to critical slope of hills. They discussed the cause and extent of slope failures in the area.

Department of Soil Conservation and watershed management GoN (1995) had published the sub-watershed management planning manual which has revealed that the landslide hazard map is important for watershed management slope, land use and land system are the factors taken into account to assess relative susceptibility of potential landslide hazard map. It has prepared the landslide hazard map. It has prepared the landslide hazard map of Kulekhani Watershed, Thotne Khola Watershed in Okhaldhunga and Tankhwa Watershed in Dhankuta, based on slope, landuse and land system.

Chapagain (1996) has studied the land use change and landslide hazard mapping of Kulekhani Watershed with the objective of analyzing land use pattern, land use change processes and to prepare the landslide hazard map. He stated that landslide has been dominant natural hazard in Kulekhani watershed with the help of GIS and field survey. He classified landslide susceptible zones into five types, stable to highly unstable by evaluation the different parameters related to landslide.

The watershed consists of upstream and downstream area. The different bio-physical and socio-economic activities on upstream areas cause landslide and mass movement phenomena. Thus, the scientific study of landslide hazard in the upstream area is essential. In this context Tianchi (1996), has studied landslide hazard and management in China. He has concluded that landslide hazard zonation mapping are essential for planner and decision maker for scientific forecasting of landslide and its management.

Dhital and Upreti (1996) have said that landslide susceptibility maps show the area likely to experience landslide hazard in the future by correlating some of the principle factors. They have reviewed the work on landslide mapping in Nepal.

Dhakal *et al.,* (1999) produced map- showing distribution of landslides of Kulekhani watershed to from aerial photo interpretation and field checking using GIS. They statistically analyzed failure rate and quantification scaling and found geology as the most important factors influencing landslide activity followed by elevation and land use.

Manandhar (2001) studied the geology of Kulekhani catchments and prepared geological map, identified the types and mechanism of landslide and mapped major landslides of the catchments area. He also analyzed slope stability and found out there properties of rock and soil.

Hasegawa et al. (2009) studied slopes along the major highways of the Central Nepal, namely Prithivi Highway, Narayangadh-Mugling Road and Tribhuvan Highway which are considered as affected by large scale landslides. The results of X-ray diffraction analysis of soils revealed that large-scale landslides along the highways have significant clay mineralization in sliding zones. The substantial hydrothermal alteration in the Lesser Himalaya during and after the advancement of the Main Central Thrust (MCT) and thereby clay mineralization in sliding zones of large-scale landslide are the main causes of large-scale landslides in the highways of central Nepal.

Karki *et al.*, (2010) studied landslide of Nallu Khola watershed and his study revealed that deforestation, unmanaged cultivation practice and rainfall are responsible factor for landslide.

# Chapter 3: Methodology

## 3.1 Research Design

Landslide is the result of combine effect of natural factors like geology, tectonic photography, hydrology, vegetation cover, and climate on the one hand and human influence in the environment on the other hand. Several factors contributing to them have been integrated together with the help of computerized GIS software ILWIS 3.0. The study follows the steps given below:

- Identification and measurement of problem
- Analysis, mapping and interpretation of result

## 3.2 Nature and Source of Data

The study is mainly based on the secondary sources of information such as map data. The verification is done by the field visit to collect the different dimensions of landslide.

### 3.2.1 Primary Data

The primary information were collected through the field visit and filling up the Landslide inventory form (Annex). Local people were consulted about the presence of absence of landslide in their respective places. Photographs of the landslide were taken, GPS points were located and the sites were pointed in the Topographic map. The field visit of Kulekhani was done on March 11-14, 2011. During the field and desk studies, landslide occurrence was indicated in the forms of polygons.

### 3.2.2 Secondary Data

The secondary source of information was collected through the various sources. As the study is mainly based upon the map data, several data layers have been regenerated from the base map. The major sources of data are:

- Topographic maps of 1992 at the scale of 1:25000 prepared by Survey Department of Government of Nepal and FINNIDA. (map no – 2785 05 A, B, C, D)
- Geological map prepared by Department of Mines and Geology

- The meteorological records of the study area published by Department of Hydrology and Meteorology/GoN of the year 1993.
- Landuse and Landslide inventory map are obtained from Department of Survey, Minbhawan, 2011.

### 3.2.3 Overlay of Data layers

The following data layers have been used to study the landslide hazard zonation within the watershed boundary:

- Land use map
- Slope map
- Aspect map:
- Relief map:
- Internal relief map:
- River distance map
- Geological map

The above data layers like Slope map, Aspect map, Relief map and Internal Relief map is generated from DEM. DEM is a type of raster GIS layer. In a DEM, each cell has a value corresponding to its elevation. DEM is generated from a contour map through a process in GIS known as “Contour Interpolation”. From these useful derivatives of Elevation such as Slope, Aspect, Internal Relief is obtained. River distance map is generated through an operation commonly known as buffering or “Distance Calculation” through raster operation.

### 3.3 Landslide Densities:

After crossing the landslide occurrence map with the parameters maps, the landslide densities of each class is calculated in ILWIS.

The Landslide density in per parameter class is calculated as:

$$\text{Density Class} = \frac{NPIX\ (Si)}{NPIX\ (Ni)}$$

Where,

NPIX (Si) = Number of pixels containing landslide in a certain parameter class.

NPIX (Ni) = Total number of pixels in a certain parameter class.

Likewise the density for entire map is calculated as:

Density Map = $\frac{\sum NPIX\ (Si)}{\sum NPIX\ (Ni)}$

### 3.3.1 Weight Values

The final weight values are calculated by taking the natural logarithm of the density in the class divided by the density in the map with the following formula:

Weight = $\ln(\frac{Dens\ Class}{Dens\ Map})$

### 3.3.2 Hazard Zonation Map

Finally combining the created weight maps of each parameter final weight map was prepared by using following formula:

Weight map = $\Sigma$ mi

Where,

mi = Weight map of each parameters

## 3.4 Application of GIS as a tool of Analysis

GIS (Geographical Information System) is defined as "an organized collection of computer hardware, software, geographic data, and personnel designed to efficiently capture tore, update, manipulate analyses and display all forms of geographically referenced information (ICIMOD, 1994).

In other words GIS is simply a computerized system for collecting, storing, retrieving, transforming and displaying geographically referenced data, the applicability of hazard assessment techniques has profited strongly. GIS as a computer based system for data capture, input, manipulation, transformation, visualization, combination, query, analysis, modeling and output with its excellent spatial data processing capacity has attracted great attention in natural disaster assessment (Carrara *et al*., 1999). With GIS, the methods for mapping landslide hazard can be briefly classified into three groups: qualitative methodologies, statistical methodologies and geotechnical model-based methodologies (Van Westen *et al*., 1997a).

Typically, landslide hazard assessment would entail the following steps (Carrara *et al.*, 1991):

- Compilation of landslide inventory of previous decades
- Acquisition/production of relevant coverage/views
- Delineation of terrain units
- Hazard modeling (ranking slope stability factors)
- GIS-coupled data processing
- Checking of preliminary results
- Output mapping

## 3.5 Quantitative Methodologies

### 3.5.1 Statistical Methods

Statistical model to determine the spatial landslide instability are used to describe the functional relationship between instability factors and the past and present distribution of slope failures (Carrara, 1983). The approach is indirect and provides quantitative results suitable to the quantitative assessment of landslide hazard. The attribution of weighted values on a subjective basis to the numerous factors that govern slope stability represents the main limitation in all the qualitative method. The solution to this problem is to adopt a statistical approach that compares the spatial distribution of landslides with the parameters being considered. The results could then be applied to areas currently free of landslide but where condition may exist for susceptibility to future instability. One of the principle advantages is that the investigator can validate the importance of each factor and decide on the final input maps in an interactive manner. Statistical analyses can be either bivariate or multivariate.

#### 3.5.1.1 Bivariate Statistical Analyses

The Bivariate Methods, as described by Van Westen (1994), are modified form of qualitative map with the exception that weights are assigned based upon statistical relationship between past landslide and various factor maps. The weighted value of the classes used to categorize every parameter is determined on the basis of landslide density in each individual class. The following operations are required as stated by Chowdhury and Aleotti (1999).

i. Selection and mapping of significant parameters and their categorization into a number of relevant classes
ii. Landslide mapping
iii. Overlay mapping of the landslide map with each parameter map
iv. Determination of density of landslides in each parameter class and definition of weighted values
v. Assignment or weighting values to the various parameter maps
vi. Final overlay mapping and calculation of the final hazard or susceptibility value of each identified land unit.

The various Bivariate methods used are given below:

- Statistical Index Method
- Certainty Factor Approach
- Landslide Susceptibility Analysis
- Probability Method or Frequency Ratio Method
- Weight of Evidence Modelling Method

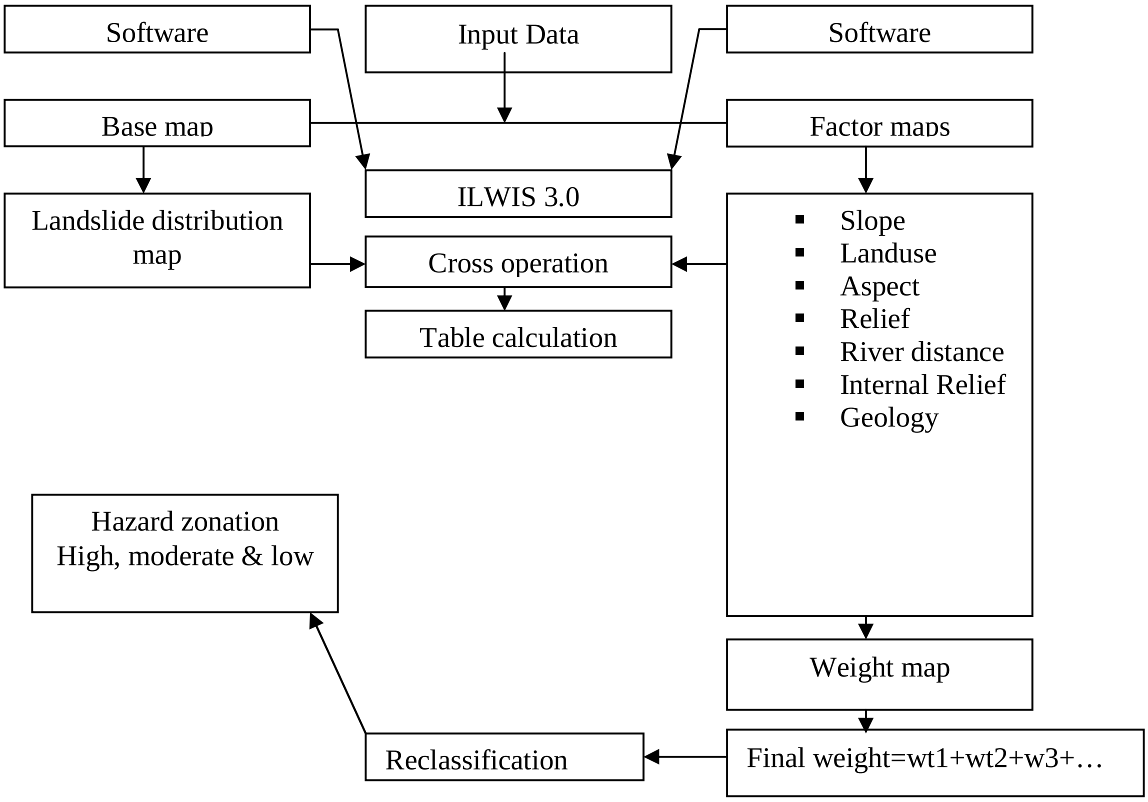


Figure 3.1: Flow chart of Bivariate Statistical method

### 3.5.1.1.1 Probability or Frequency Ratio Method

It is common to assume that landslide occurrence is determined by landslide related factors, and that future landslide will occur under the same conditions as past landslides. Using this assumption, the relation between landslides occurring in an area and landslide related area can be distinguished from the relation between landslides not occurring in an area and the landslide related factors. It can be expressed as a Frequency Ratio that represents the quantitative relationship between landslide occurrences and different causative parameters. The formula for the calculation by frequency ratio is as follows:

$$W_{ij} = \frac{f^{*}_{ij}}{f_{ij}} = \frac{A^{*}_{ij}}{A_{ij}} \text{ X } \left(\frac{A - A^{*}}{A_{ij} - A^{*}_{ij}}\right) \qquad \text{(Eqn – 1)}$$

Where,

$W_{ij}$ = Weight given to a certain class i of parameter j

$f^{*}_{ij}$ = Frequency of the observed landslide in the class i of parameter j

$f_{ij}$ = Frequency of the non-observed landslide in the class i of parameter j

$A^{*}_{ij}$ = Area of landslides in certain class i of parameter j

$A_{ij}$ = Area of certain class i of parameter j

$A^{*}$ = Total area of landslide in the entire map

A = Total area of entire map

Therefore, the greater the ration above unity, the stronger the relationship between landslide occurrence and the given factor's attribute, and the lower the ratio below unity, the lesser the relationship between landslide occurrence and the given factor's attribute (Lee and Pradhan, 2006).

Hence, probabilistic approaches are based on the observed relationship between each factor and the distribution of observed landslides. The probability method uses the frequency ratio to rate the relationship between landslides and each factor's type.

#### 3.5.1.1.2 Statistical Index Method

The statistical Index Method is a Bivariate Statistical Analysis introduced by Van Westen (1997b) for landslide susceptibility analysis. In this method, a weight value for a parameter class is defined as a natural logarithm of the landslide density in the class divided by landslide density in the entire map.

The following is the formula for calculating the density of each parameter class such as a certain geological unit or a certain slope class.

$$W_{ij} = \ln \frac{f_{ij}}{f} = \ln \left( \frac{A^{*}ij}{A_{ij}} \text{ X } \frac{A}{A^{*}} \right) \qquad \text{(Eqn – 2)}$$

Where,

$W_{ij}$ = Weight given to a certain class i of parameter j

$f_{ij}$ = Landslide density within the class i of parameter j
f = Landslide density within the entire map
$A^*_{ij}$ = Area of landslides in certain class i of parameter j
$A_{ij}$ = Area of certain class i of parameter j
$A^*$ = Total area of landslide in the entire map
A = Total area of entire map

The $W_{ij}$ value in equation 2 is only calculated for classes that have landslide occurrences. In the case of no landslide occurrence in the certain class of the parameter, the $W_{ij}$ is assigned as Zero (Van Westen, 1997b; Yalcin, 2008). This means that parameter class having no landslide will have no correlation with landslide inventory. In this study, every parameter is crossed with the landslide map and the density of the landslide in each class is calculated.

### 3.5.1.1.3 Landslide Susceptibility Analysis

Landslide susceptibility analysis is a simple and useful bivariate method to determine the importance of different variables for landslide occurrence. To evaluate the influence of each variable, weighting factors are determined, which compare the calculated density with the overall density in the area (Suzen and Doyuran, 2004). The following formula is used to calculate:

$$W_{ij} = 1000(f_{ij} - f) = 1000\left(\frac{A^*{ij}}{A_{ij}} - \frac{A^*}{A}\right) \qquad \text{(Eqn – 3)}$$

Where,
$W_{ij}$ = Weight given to a certain class i of parameter j
$f_{ij}$ = Landslide density within the class i of parameter j
f = Landslide density within the entire map
$A^*_{ij}$ = Area of landslides in certain class i of parameter j
$A_{ij}$ = Area of certain class i of parameter j
$A^*$ = Total area of landslide in the entire map
A = Total area of entire map

#### 3.5.1.1.4 Weight of Evidence Modelling

Weight of evidence (WOE) is a quantitative 'data-driven' method used to combine datasets. The method, first applied in medicine (Spiegelhater and Kill-Jones, 1984). Then Bonham-Carter et al. (1990) used this method to identify the mineral potential in 1990. The WOE application for geology in which uses the log-linear form of the Bayesian probability model to estimate the relative importance of evidence by statistical means was given later by Bonham-Carter (1994). Since then, the WOE modeling method for landslide susceptibility mapping was processed in many case studies (Van Westen, 1993; Sentz and Ferson, 2002; Lee *et al.*, 2002).

Prior probabilities and posterior probabilities are the most important concepts in the Bayesian approach. The probability P is usually determined empirically with knowledge about the occurrence of an event D in the past under equal conditions, and is addressed as prior probability P{D}. This probability can be modified with data B that influenced the probability and are gained from surveys, experiments or analyses (Malczewski, 1999). When the evidences are integrated into the calculation of the probability, it is addressed as conditional or posterior probability P{D|B}. Bayes theorem can be written as:

$$P\{D \mid B\} = \frac{P\{D\} \times P\{B \mid D\}}{P(B)} \qquad \text{(Eqn-4-1)}$$

By overlaying landslide locations with each evidence (causative factor), the statistical relationship can be measured between them, and assessed as to whether and how significant the evidence is responsible for the occurrence of past landslides (Neuhäuser and Terhorst, 2007). On the other hand, WOE model is fundamentally based on the calculation of positive and negative weights ($W^+$ and $W^-$), the magnitude of which depends on the measured association between the response variable (the landslides) and the predictor variables (causative factors). Modified Bonham-Carter's definition of positive and negative weights ($W_{ij}^+$ and $W_{ij}^-$) of evidence respectively of the j$^{th}$ class of i$^{th}$ landslide evidential map are calculated as follows:

$$W_{ij}^{+} = \log_e \frac{P(B \setminus D)}{P(B \setminus \bar{D})}$$ (Eqn-4-2)

$$W_{ij}^{-} = \log_e \frac{P(\bar{B} \setminus D)}{P(\bar{B} \setminus \bar{D})}$$ (Eqn-4-3)

Where

B - Presence of the landslide evidential feature.

D - The number of landslide belonging in the evidential feature

$\bar{B}$ - The total area on the map where the evidential feature is absent

$\bar{D}$ - The number of landslide not belonging in the evidential feature.

In landslide susceptibility mapping, the contrast ($C_{ij}$), measures and reflects the spatial association between the evidence feature and landslide occurrence. Therefore, the contrast is a measure of favorability of a feature as landslide susceptibility.

$$C_{ij} = W_{ij}^{+} - W_{ij}^{-}$$ (Eqn-4-4)

Where,

$C_{ij}$ is the contrast value of the j<sup>th</sup> class of i<sup>th</sup> evidential map.

$C_{ij}$ is positive for a positive spatial association, and negative for a negative spatial association. The contrast is set to the rating of each factor, because the contrast is related to landslide probability.

Based on Eqn (4-2) and Eqn (4-3) the weights of evidence can be written in the numbers of pixels as follows:

$$W_{ij}^{+} = \log_e \left( \frac{\frac{Npix_1}{Npix_1 + Npix_2}}{\frac{Npix_3}{Npix_3 + Npix_4}} \right)$$ (Eqn-4-5)

$$W_{ij}^{-} = \log_e \left( \frac{\frac{Npix_2}{Npix_1 + Npix_2}}{\frac{Npix_4}{Npix_3 + Npix_4}} \right)$$ (Eqn-4-6)

In order to calculate the weights using Eqn (4-5) and Eqn (4-6), it is needed to create following informations:

nmap = total number of pixels in the map
nslide = number of pixels with landslide in the map
nclass = number of pixels in the class
nslclass = number of pixels with landslide in the class

The values needed for the weight formulas are:

$Npix_1$ = nslclass
$Npix_2$ = nslide – nslclass
$Npix_3$ = nclass – nslclass
$Npix_4$ = nmap – nslide – nclass + nslclass

The final weight is then calculated as:

$$Wmap = W_{ij}^{+} + W^{-}_{total} - W_{ij}^{-} \qquad \text{(Eqn-4-7)}$$

### 3.5.1.1.5 Certainty Factor

The basic principles of certainty factor (CF) theory were first introduced in MYCIN, an expert system for the diagnosis and therapy of blood infections and meningitis (Shortliffe and Buchanan, 1975). For landslide hazard modeling, certainty factor model has been deeply considered and experimentally investigated.

Employing the CF theory for landslide problem, CF as a function of probability of landslide hazard was defined by Chung and Fabbri (1998), Binaghi *et al.*, (1998), and Lan *et al.*, (2004) as follows:

$$CF_{ij} = \begin{cases} \dfrac{f_{ij}-f}{f_{ij}(1-f)} & \text{if } f_{ij} \geq f \\[2ex] \dfrac{f_{ij}-f}{f(1-f_{ij})} & \text{if } f_{ij} \leq f \end{cases} \qquad \text{(Eqn-5)}$$

Where,

$CF_{ij}$ = Certainty Factor given to a certain class i of parameter j

$f_{ij}$ = Landslide density within the class i of parameter j

f = Landslide density within the entire map

Where $f_{ij}$ is the conditional probability having a number of landslide event occurring in class and f is the prior probability having total number of landslide event occurring in the study area.

Certainty factor is a number to measure the expert's belief. The range of the certainty factor is [-1, +1]. The minimum -1 means definitely false and +1 means definitely true. Positive value means an increasing certainty in landslide occurrence, while negative value corresponds to a decreasing certainty in landslide occurrence. A value close to 0 means that the prior probability is very similar to the conditional one, so it is difficult to give any indication about the certainty of the landslide occurrence.

# Chapter 4: Study Area

## 4.1 Description of the Study Area

### 4.1.1 Location

The Kulekhani watershed lies in the north eastern part of Makawanpur district of Central Development Region. It is situated about 30 km. west of the Kathmandu valley. It lies within the latitude of N 27° 35′ to N 27° 45′ and E 85° 00′ to E 85° 15′ longitude. It contains 5 Village Development Committees viz. Bajrabarahi, Chitlang, Daman, Markhu and Palung. The surface area of the watershed is approximately 124.25sq.km. It lies in the Mahabharat range of Lesser Himalaya.

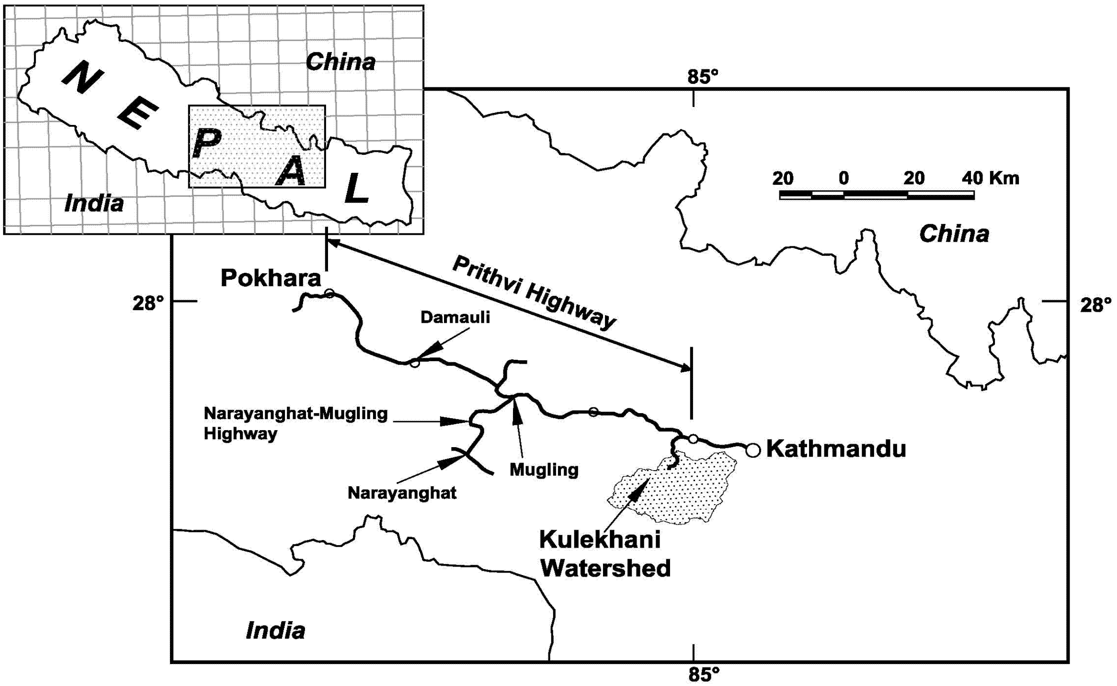


Fig4.1: Location of the Study Area (A)

Fig 4.2: Study Area through Map Google (The delineated and shaded portion)

### 4.1.2 Altitude

The watershed area ranges from 1500masl to 2621masl elevation. The Kulekhani Dam or Indra Sarobar lies at the attitude of 1500masl and the highest relief is at Palung. As it lies in the Mahabharat range most of the part have rugged terrain and characterized by steep slope. The physiographic features trend to west-northwest to east-southeast direction.

### 4.1.3 Geology

The geology of Kulekhani watershed is associated with the Phulchoki sub-group and Bhimphedi sub-group of Kathmandu group. The Phulchoki sub-group consist Chitlang formation, Chandragiri formation, Sopyang formation, Tistung formation, and Bhimphedi sub group consist Markhu formation, Sarungkhola formation and Maksang formation within the study area. Apart from these, the granite of Himal group and Siwalik group geology are also found. The rocks like, limestone, quartzite, phyllites, schists, slate, granite are found here. Some brief discussion is given below on different geology of the study area:

#### 4.1.3.1 Bhimphedi Group

The Bhimphedi group contains schist, quartzite and marble. It consists of following formation:

- **Chisapani Quartzite**

This formation is made up of white or pale green clean quartzite. The quartizite is very fine grained and contains sericite as fine partings. It extends from saddle of Ghartikhola gaun and it is well exposed along the left bank of the Ghartikhola (Stocklin and Bhattarai, 1981).

- **Kulikhani Formation**

Kulikhani formation is characterized by quartz and mica in proportion varying from layer to layer, resulting in alternation of more or less micaceous quartzite and more or less quartzitic schists (Stocklin and Bhattarai, 1981). It is found along the Gharti khola, Palung khola, Andheri khola, Tistung khola, and along Tribhuwan Highway near Okhargaun.

- **Markhu Formation**

It is composed of mixed lithology, consist of schists, quartzite and carbonates in varying proportions. This formation is distributed along Andheri khola, Tistung khola, Palung khola, at Markhu, at Bhotekhoriya bhanjyang.

- **Tistung Formation**

The Tistung formation consists essentially of slates, phyllites and metasandstone. It is found along some parts of Tribhuwan Highway, and also Chitlang khola, Bisinkhola, Tistung khola, Andheri khola.

#### 4.1.3.2 Phulchauki Group

The Phulchauki group mainly consists of limestones and subordinates zone of shales and sandy rocks (Stocklin and Bhattarai, 1981).

- **Sopyang Formation**

It is transitional zone between fine rocks of the Tistung Formation and thick Chandragiri limestone, with mixed lithology of both (Stocklin and Bhattarai, 1981). It is mainly found in Chitlang khola.

- **Chandragiri Limestone**

It is the most prominent formation of Phulchauki group. The main rock is a yellow or brown weathered limestone. In the study area, this formation is found along the Chitlang khola, Bisinkhel.

- **Chitlang Formation**

The Chitlang formation mainly consists of dark, purplish, soft weathered slates. The formation is found along the Chitlang khola and at Bisinkhel bhanjyang. Along the Chitlang khola, the formation contains phyllites. At Bisinkhel bhanjyang, slate and phyllite are found.

#### 4.1.3.3 Palung Granite

Palung granite is mainly intruded in the rocks of the Chisapani quartzite in the Gharti khola side and in the Kulikhani formation. It is found in the Palung khola, Gharti khola, Shikharkot, Daman, Simbhanjyang, Kiteni.

### 4.1.4 Drainage

The Kulekhani river originates in the Mahabharat Range about 30km west of the Kathmandu and 5 km west of Palung. It flows in south-east direnction until it mixes the Kulekhani reservoir. The main draining river in the Kulekhani watershed is Palung khola. The Phedigaun Khola and Gharti Khola join near Palung and it becomes Palung Khola. The dendritic pattern of river consists many tributaties,. Bishenkhel Khola and Chitlang Khola are other major tributaries from the north. Similarly Kitini Khola, Chalkhu and Darkot khola are other major tributaries from the south. The Kulkhani reservoir with an area of almost 2km$^2$ is situated in the South-East corner of the watershed.

### 4.1.5 Climate and Rainfall

The watershed area consists of warm temperate and cool temperate climatic region. The warm temperate climate is in the lower altitude generally below 2100 meters elevation and cool temperate climate is found above the altitude of 2100 meters. The disaster struck year of 1993 especially July has high rainfall. The rainfall data of 1993 of the different station in an around the study area is given in Annex (Table 3). Also the figure below shows the average annual precipitation of the Kulekhani Watershed and around its proximity place.

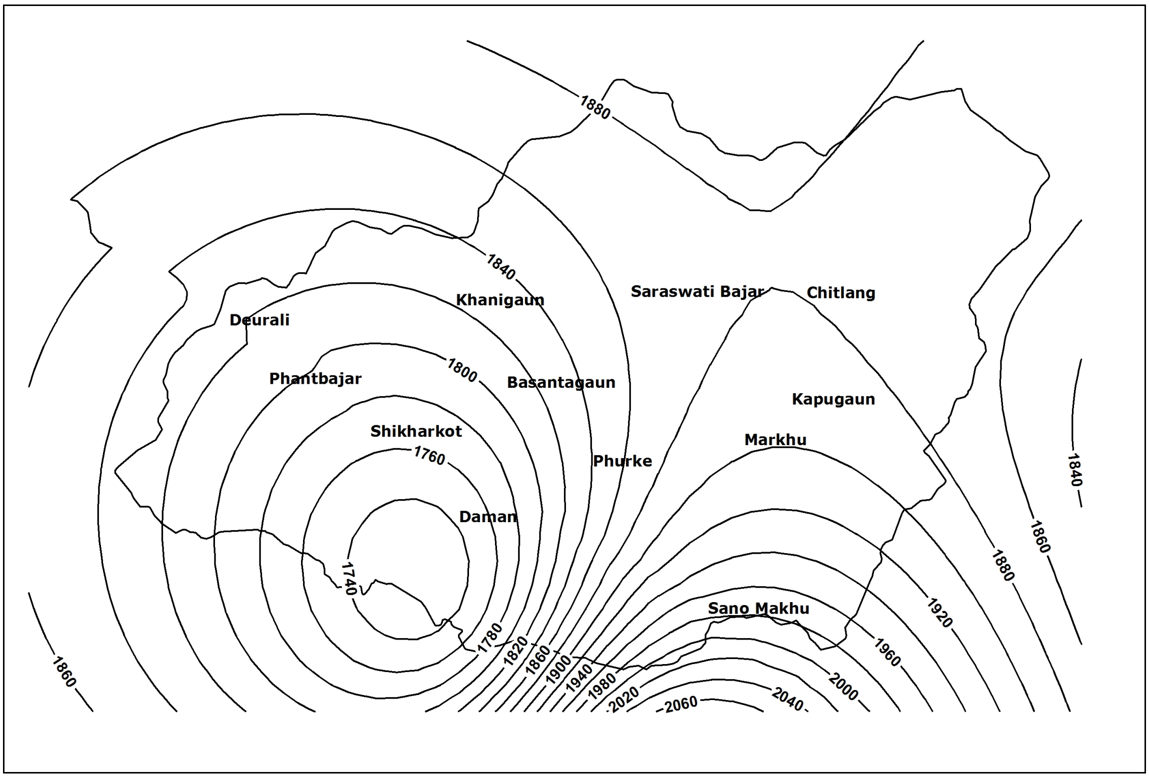


Fig 4.3: Average Annual Precipitation of Kulekhani Watershed

### 4.1.6 Natural Vegetation

The deciduous and coniferous forests are found here. The deciduous mixed forest is found in the lower altitude generally up to the elevation of 2100 meters. The major species of this type of forest are: Utis (*Alnus nepalensis*) and Katus (*Castanopsis indica*). Apart from these, the watershed area is famous for some important types of herbs vegetation i.e., majhito (*Rubia* *cardifolia*), Chiraito (*Swertia chiraito*), Jeewanti (*Demotrichum tibritum*), Kutki (*Picrorhiza kurroa*), Kurilo etc. Vegetation around the confluence of Gharti khola with Palung Khola is poor because of the damage caused by disastrous events. Dominant trees are isolated tall trees of *Populus sp.*, some clumps of *Salix babylonica* and *Sambucus sp*., along the river course. *Schima wallichi*, *Pinus roxburghii*, *Rhododendron arboretum* are the important type of coniferous forest found along the watershed area.

### 4.1.7 Landuse/Landcover

The area largely consists of forest and cultivation area. Almost 43% of the area of watershed is covered by forest. The forest consists of Utis (*Alnus nepalensis*), Katus (*Castanopsis indica*). The forests of the study area are found between altitudes 1500 and 2500 m. The forest type of the watershed is Schima - Castanopsis forest (700-2000 m), Pinus Roxburghii forest (1000-2200 m), and Alnus woods (1000-3000 m) (Stainton, 1972). Rhododendrons are also frequently present in the watershed area. Other species found are *Populus sp.* and *Salix babylonica* and *Sambucus sp.* As the main economy of the area is cultivation, total area of agricultural activities in nearly 49%. The next is followed by bush which consists of 8% of the total area. The agricultural land is increasing at rapid rate at the cost of forest and other open places. The water body consists of nearly 1% with Indra Sarobar and other contributing rivers and streams.

## 4.2 Disasters in the Study Area

Natural disaster had been a regular phenomenon threatening the area. Fragile geology, steep relief and exceptional meteorological events, the natural calamities frequently occur in Nepal. In past few years, the study area experienced several disasters.

Major Landslides and Floods Associated with High Intensity Rain in the Study Area.

| Places | Year of major events |
|---|---|
| Daman-Palung | 1915, 1954, 1979 and 1993 |
| Phedigaun | 1954, 1970, 1971, 1974, 1985 and 1993 |

Source: Dhital *et al.*, (1993)

# Chapter 5: Result

## 5.1 Factor Map Preparation

Seven relevant factors are selected as the input for the models of landslide susceptibility mapping in the study area i.e. Slope, Aspect, Relief, Internal Relief, Distance from river and stream, Land use and Geology.

All complied information is entered in the GIS environment together for GIS database and produced the final inventory map (Fig 5.1). The study area covers an area of 124.24 km$^2$ and is mapped in the scale 1:25,000 where 309 landslides were identified.

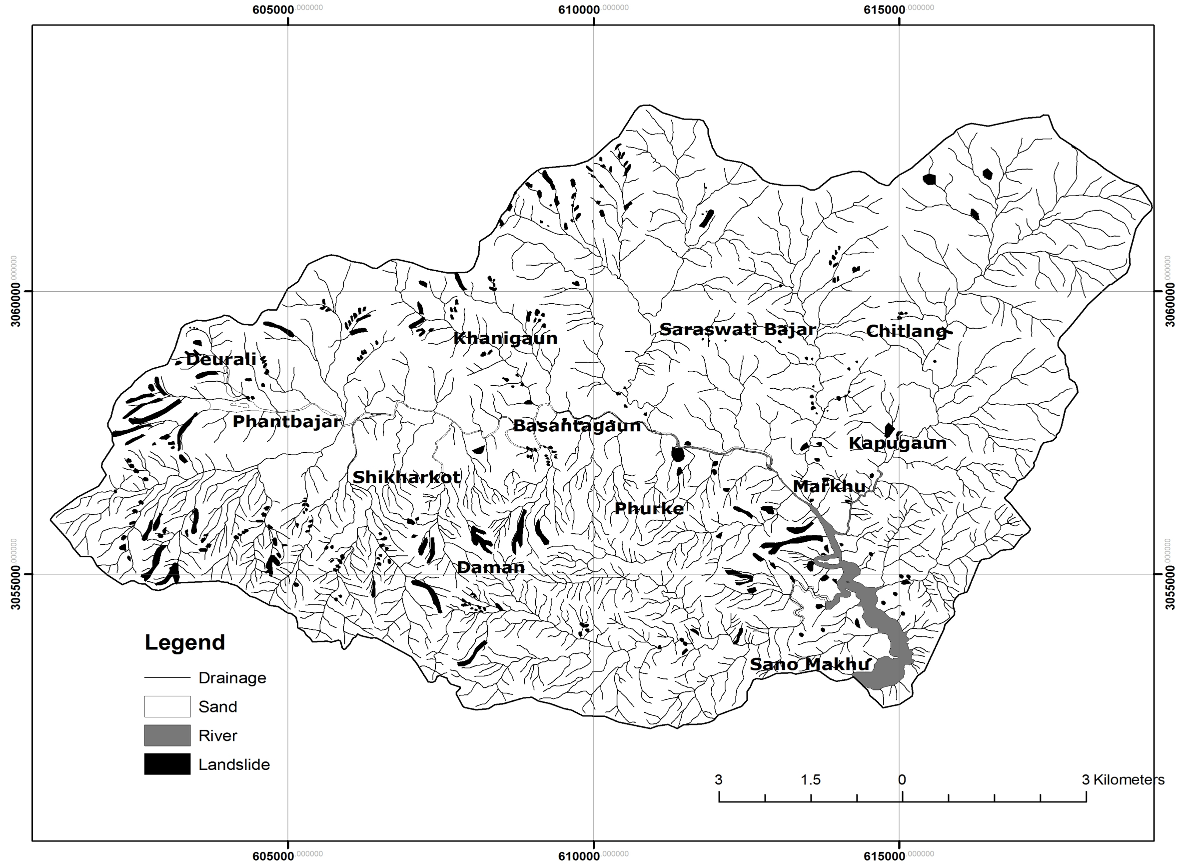


Fig 5.1: Landslide Inventory Map

### 5.1.1 Slope Factor

It is apparent that slope is the principle factor in affecting the landslide occurrence. The steeper the slope, the more risk of landslide due to the higher shear induced by gravity. The slope map of Kulekhani watershed is derived from DEM using the slope function in ILWIS 3.0. The slope map is in the form of raster map with the pixel size of DEM. A map of slope classes is generated by classifying the slope angles into five different classes (Fig: 5.2) i.e. <15°, 15-25°, 25-35°, 35-45°, >45°. The slope class of <15° contribute the largest percentage i.e. 26.93% followed by 25-35° encompassing 26.63%.  Statistical analysis indicates that the slope classes of 15-25° and 25-35° constitute the larger % of landslide which is 24% and 33.8% respectively. The slope class of 35-45° also contribute approximately 19% followed by the class of <15° and >45°.

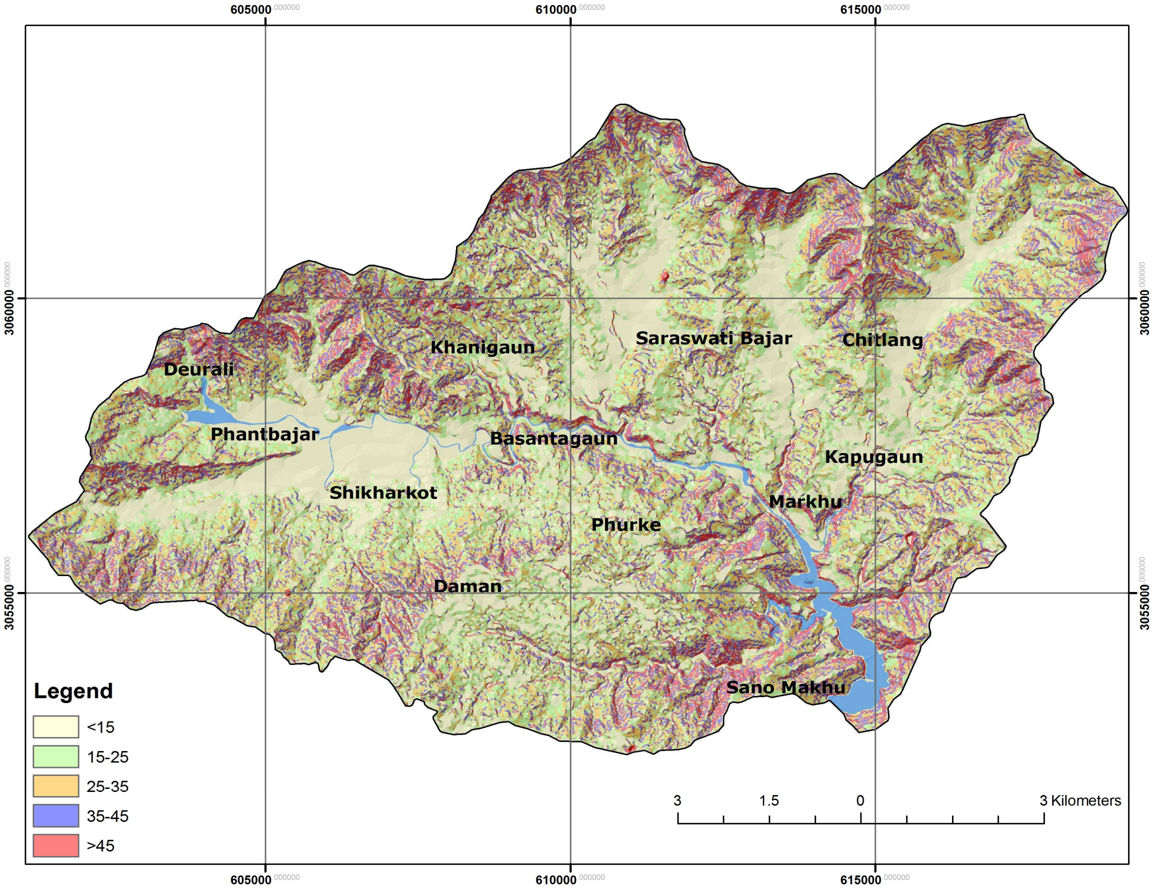


Fig 5.2: Map of Slope Classes in the study area

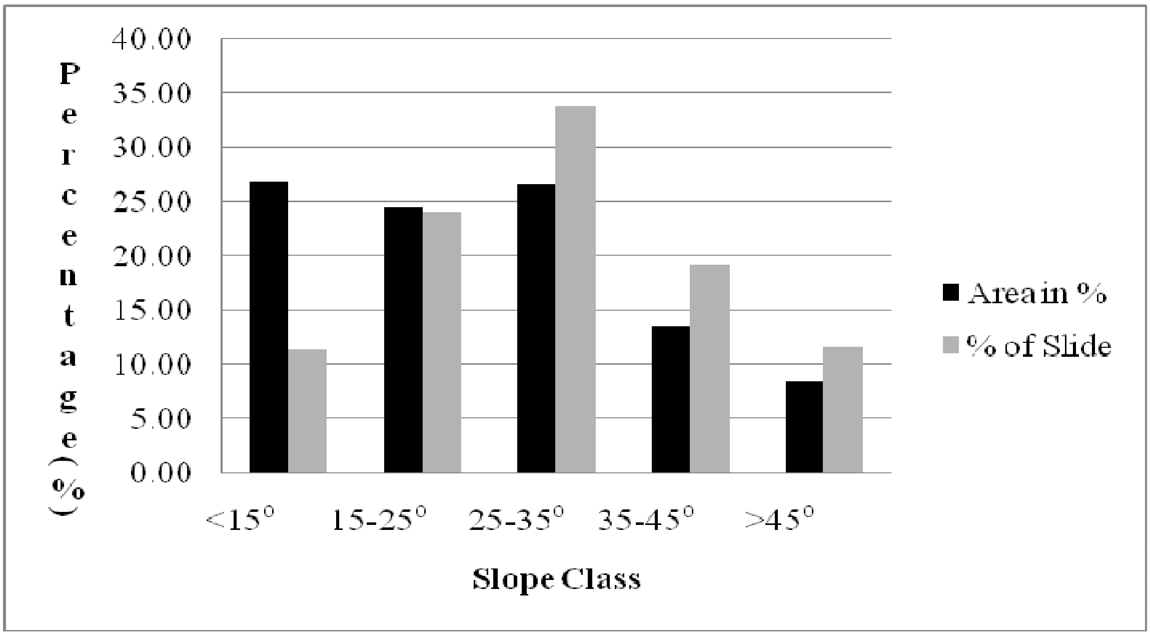


Fig 5.3: Percentage of Slope Classes and landslide occurrence

### 5.1.2 Aspect Factor

The windward and the leeward faces as well as Northern and Southern slopes of a mountain differ in their climatic conditions, it is because of the difference in the amount of rainfall and sunshine received which in turn controls the diversity, density, and the distribution of vegetation in the area. All these factors control the soil type, drainage type and susceptibility to mass wasting over an area. . A map of aspect classes is generated by classifying the aspect into eight different classes i.e. N, NE, E, SE, S, SW, W, and NW (Fig 5.4). An aspect map shows to which side a slope is directed. From the statistical analysis, east facing slope constitute the larger percentage of landslide i.e. 23.87% which then followed by N and NE which have 17.2% and 15.58% respectively. The least landslide occurred in South West facing slope i.e. 5.13%. Figure 5.5 shows the percentage of different aspect classes with landslide occurrence.

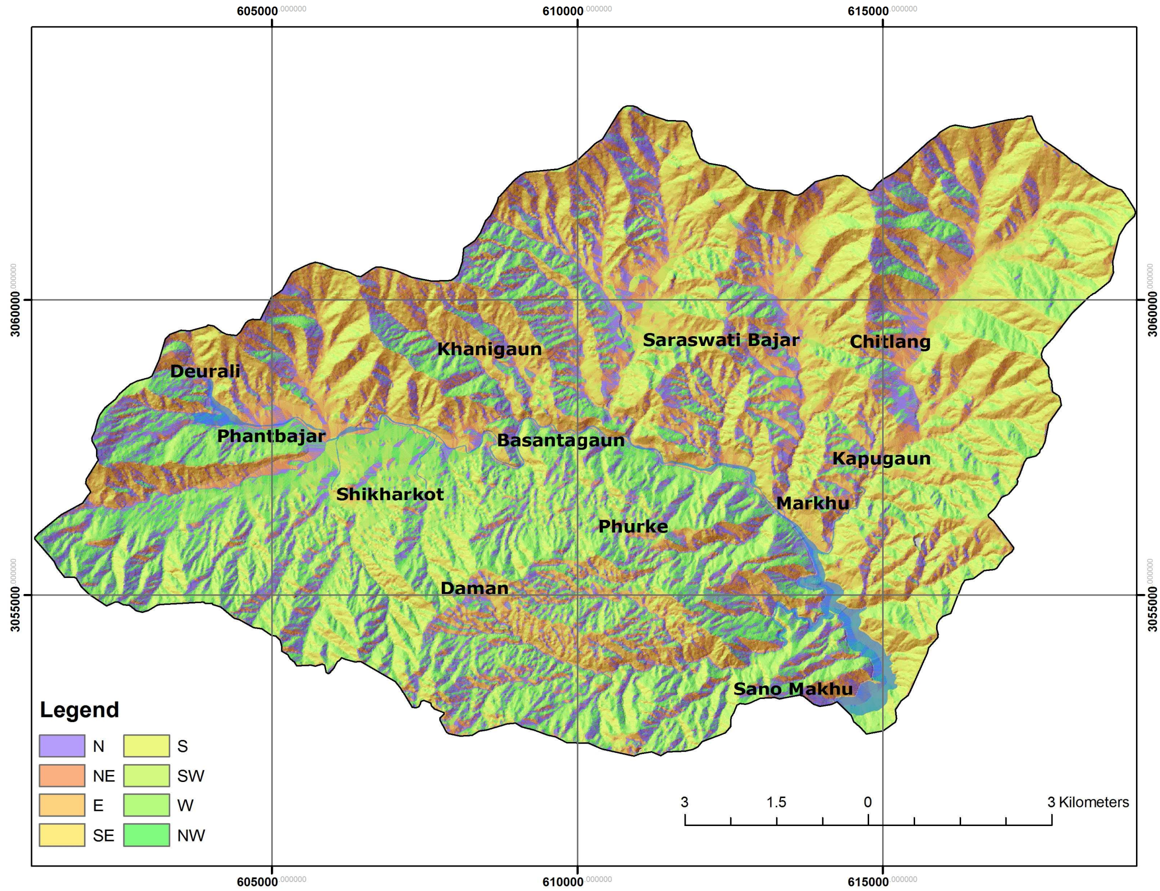


Fig 5.4: Map of Aspect classes in the study area

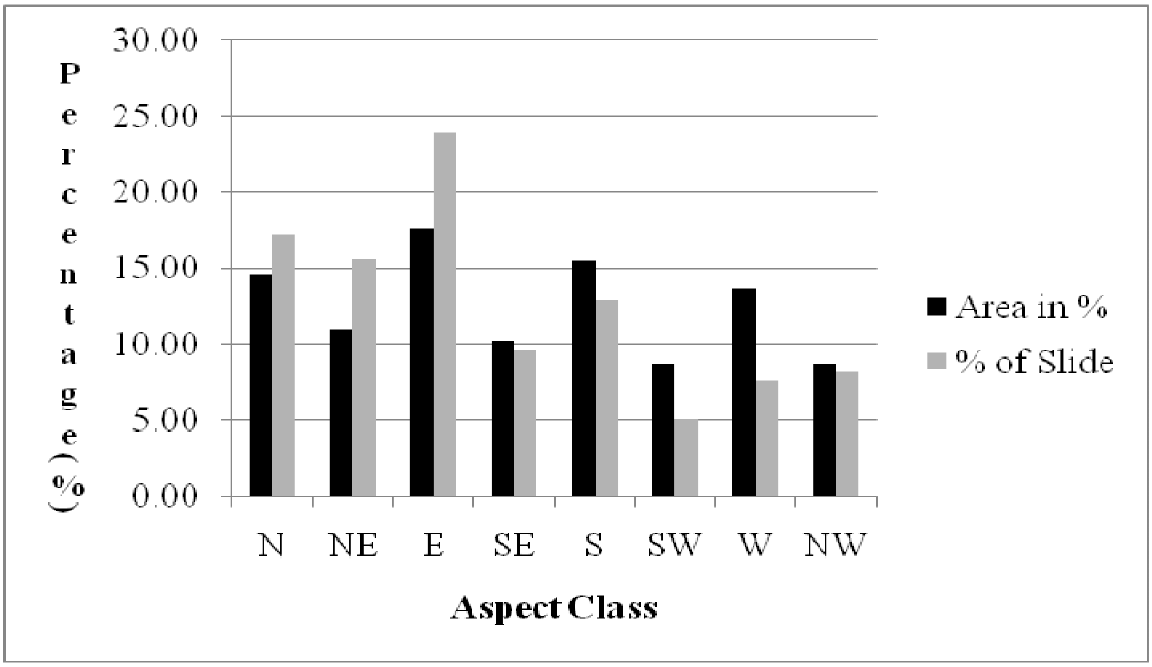


Fig 5.5: Percentage of Aspect Classes and landslide occurrence

### 5.1.3 Relief Factor

Elevation influences to landslide are often displayed as an indirect relationship or by means of other factors. The weathering factor that plays an important role in land sliding is closely related with elevation. The surface relief is the variation in height of a land surface. Different reliefs have different climatic conditions. Another important aspect relating relief and landslide hazard is that construction activities like roads are preferentially built along the same relief. It is therefore why landslide hazards in an area are observed more or less on the same relief. On the basis of polyline contour of 20m interval, the DEM was derived from "Contour Interpolation" using ILWIS 3.0 software. Then from DEM, relief was derived from "Slicing Operation" (Fig 5.6). Four different classes of relief factor were attributed viz. <1700m, 1700-2000m, 2000-2300m, >2300m. Almost half of the landslide in the study area is in the class of 2000-2300m i.e. 48.52%. Figure below (5.7) shows the percentage of different relief classes with landslide occurrence:

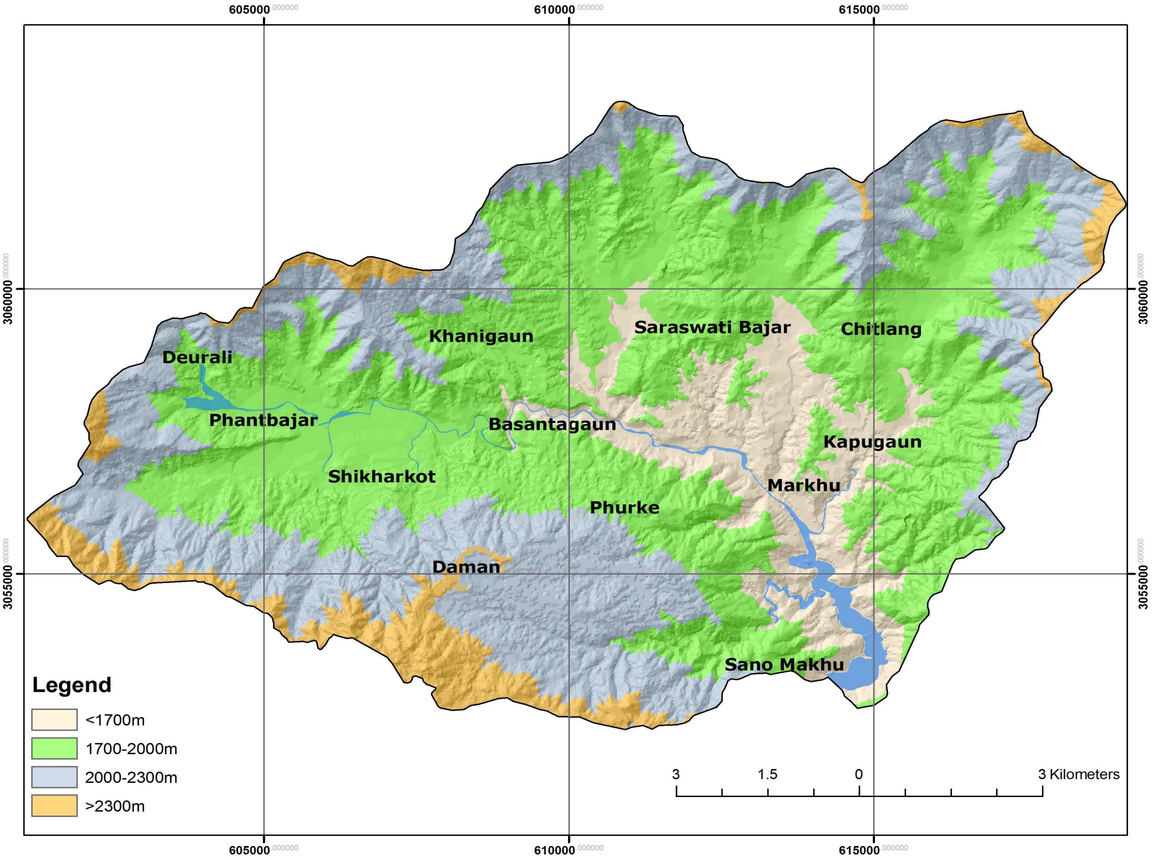


Fig 5.6: Map of Relief Classes in the study area

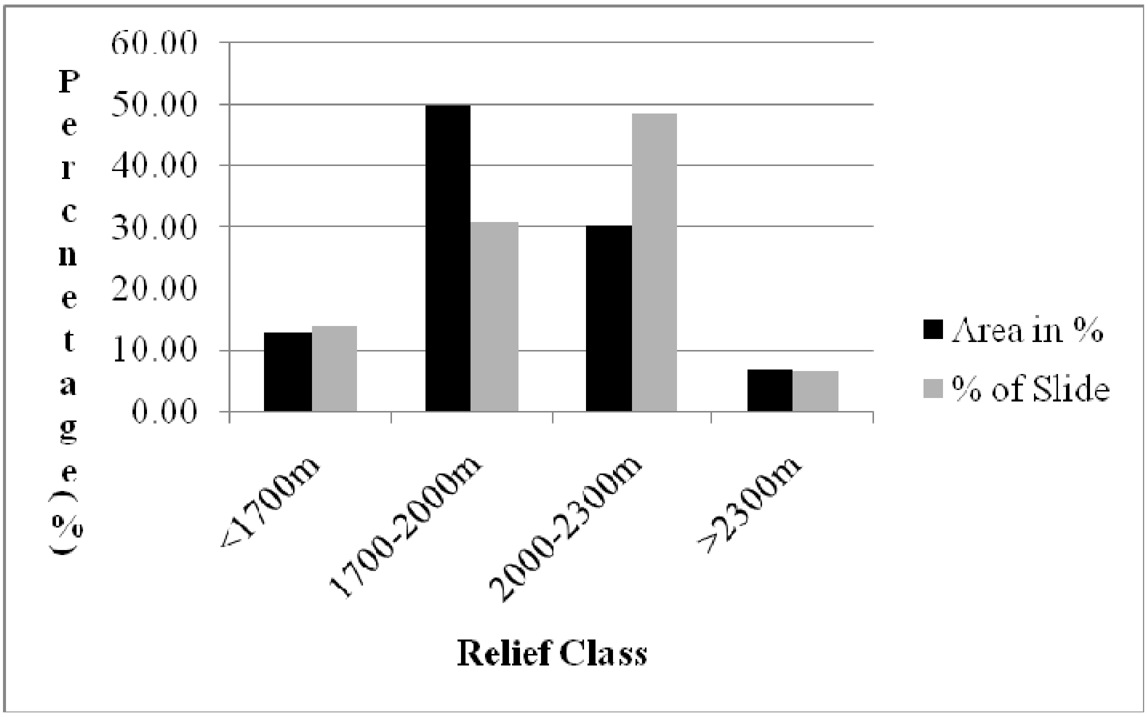


Fig 5.7: Percentage of Relief Classes and landslide occurrence

### 5.1.4 Internal Relief

Internal Relief map shows the local relief that is the local difference in height within a unit area. It indicates the potential energy for erosion and mass movement. Relative relief shows the major breaks in the slopes of the study area. Relative relief portrays the difference in elevation at a given point. The factor of safety deceases with increase in height. Thus, for two slopes having identical geo-mechanical and geometrical parameters except for height, the higher slope will be more susceptible to landslides. Run-off is higher and infiltration is lower in areas of steeper topography. Six categories of relative relief in meter have been chosen for hazard evaluation i.e. <10m, 10-20m, 20-30m, 30-40m, 40-50m, >50m(Fig 5.8). Internal relief is derived from product of DEM max and DEM min which in turn is derived from DEM. The larger proportion of landslide was found in the 20-30m and 30-40m internal relief. The internal relief class with landslide distribution is shown in the figure 5.9.

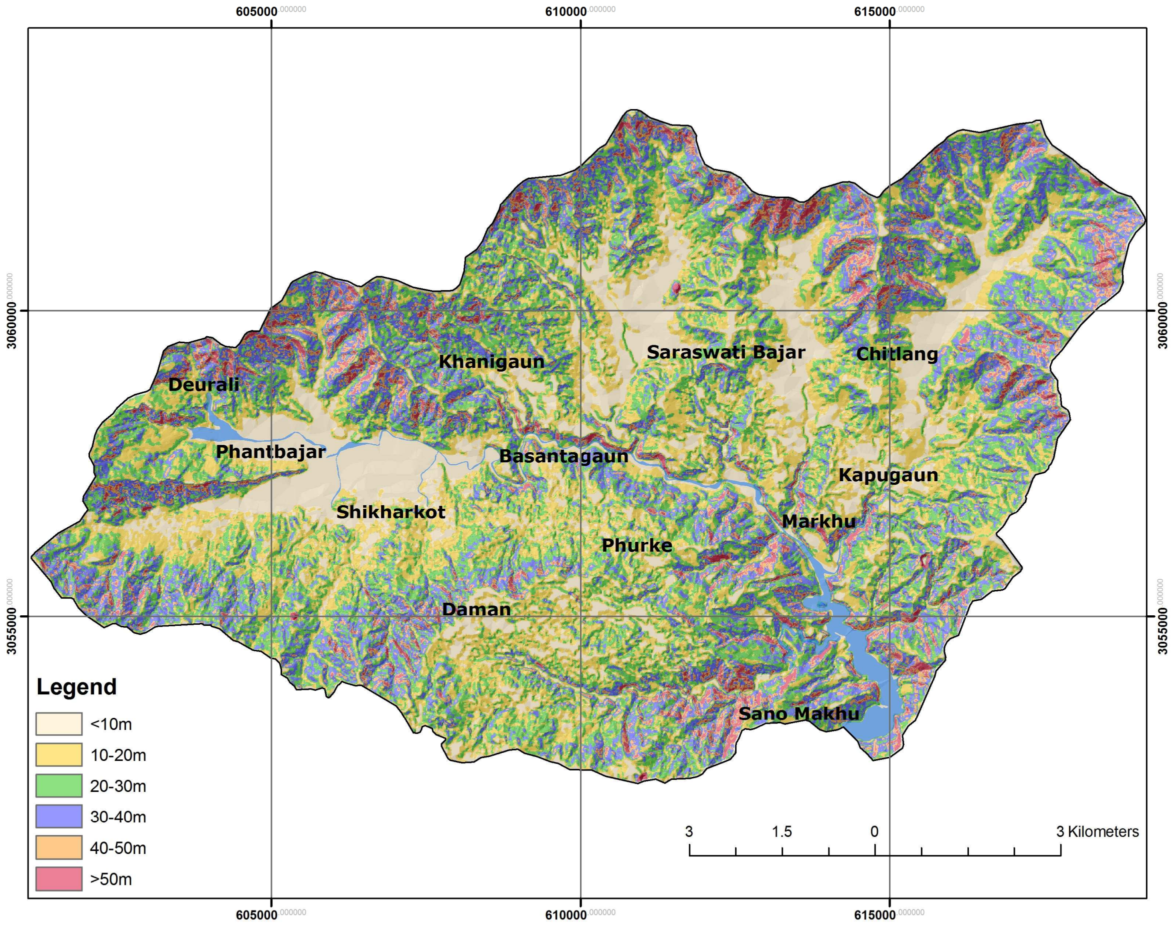


Fig 5.8: Map of Internal Relief classes in the study area

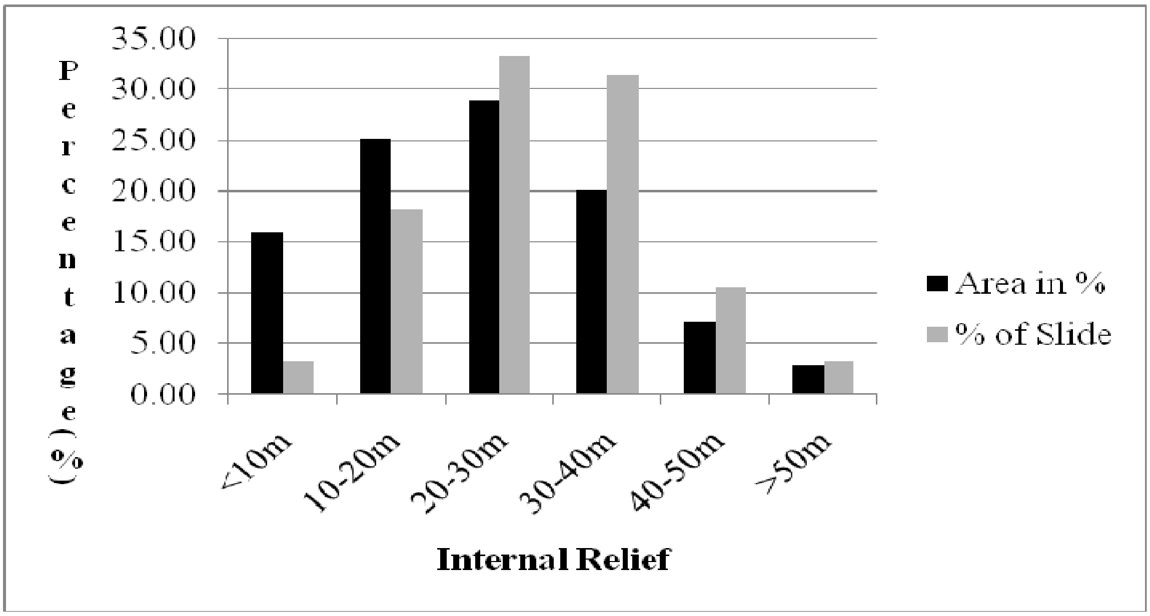


Fig 5.9: Percentage of Internal Relief classes with landslide distribution

### 5.1.5 River Distance

Runoff is an important factor to trigger landslide mechanism. Studies have shown that proximity to drainage lines of intensive gully erosion is an important factor controlling the occurrence of landslide (Pachauri et. al 1992). Hence in order to model the influence of runoff on landsliding, the distance from river was taken into account. On the basis of river and stream on the topographic map, a map of distance from river is calculated by buffering in ILWIS. Then a class map was created by subdividing the distance from river range values into 4 sub-classes i.e. <25m, 25-50m, 50-100m, >100m (Fig 5.10). Most of landslide area occurred in the area which is in proximity with the river. The next was followed by the one which is farthest to the river. The figure below (Fig 5.11) shows the percentage distribution of area of slope class and landslide occurrence in those classes:

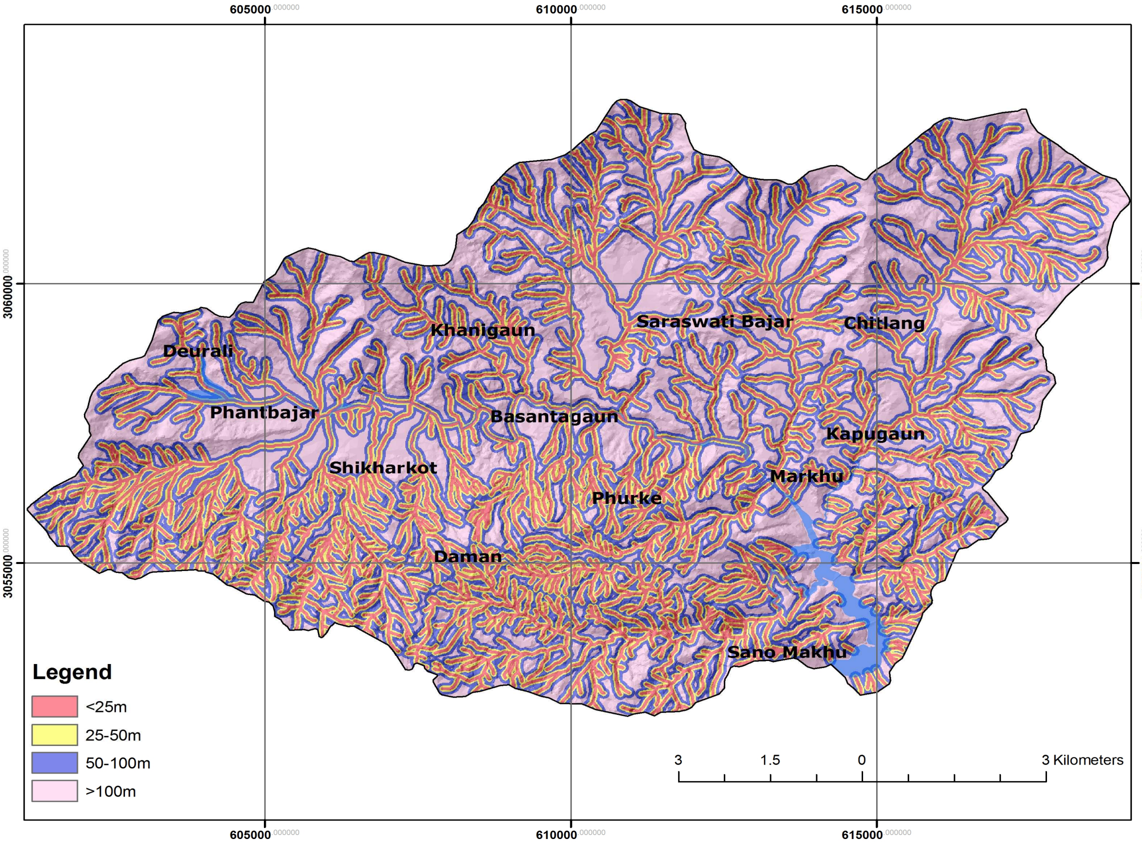


Fig 5.10: Map of River Distance classes in the study area

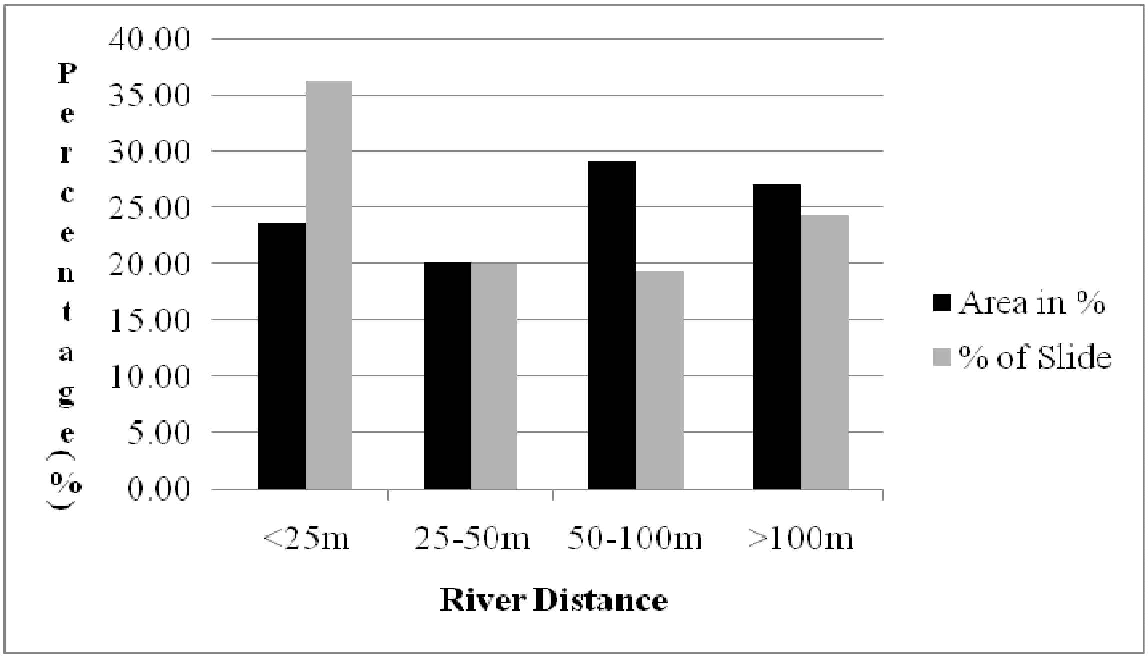


Fig 5.11: Percentage of River Distance class with landside distribution

### 5.1.6 Landuse Factor

The landuse has also significant role in the stability of soil slope. The land covered by forest regulates continuous water flow and water infiltration regularly where as the cultivated land affects the soil slope stability due to saturation of covered soil. The landuse pattern of the study area is categorized into Bush, Barren, Cultivation, Forest, Grass, Nursery, Sand and Water body. In area with bare hills or shrubs, the slope stability strongly reduces due to the lack of root cohesion, and increase possibly of soil moisture, etc. Therefore, erosion processes are enhanced, increasing local landslide hazard. The landslide distribution with the different land cover is given in the figure below (Fig 5.13) with the landuse map. The highest proportion of landslide occurred in the forest area followed by cultivable land i.e. 52.62% and 36.28% respectively.

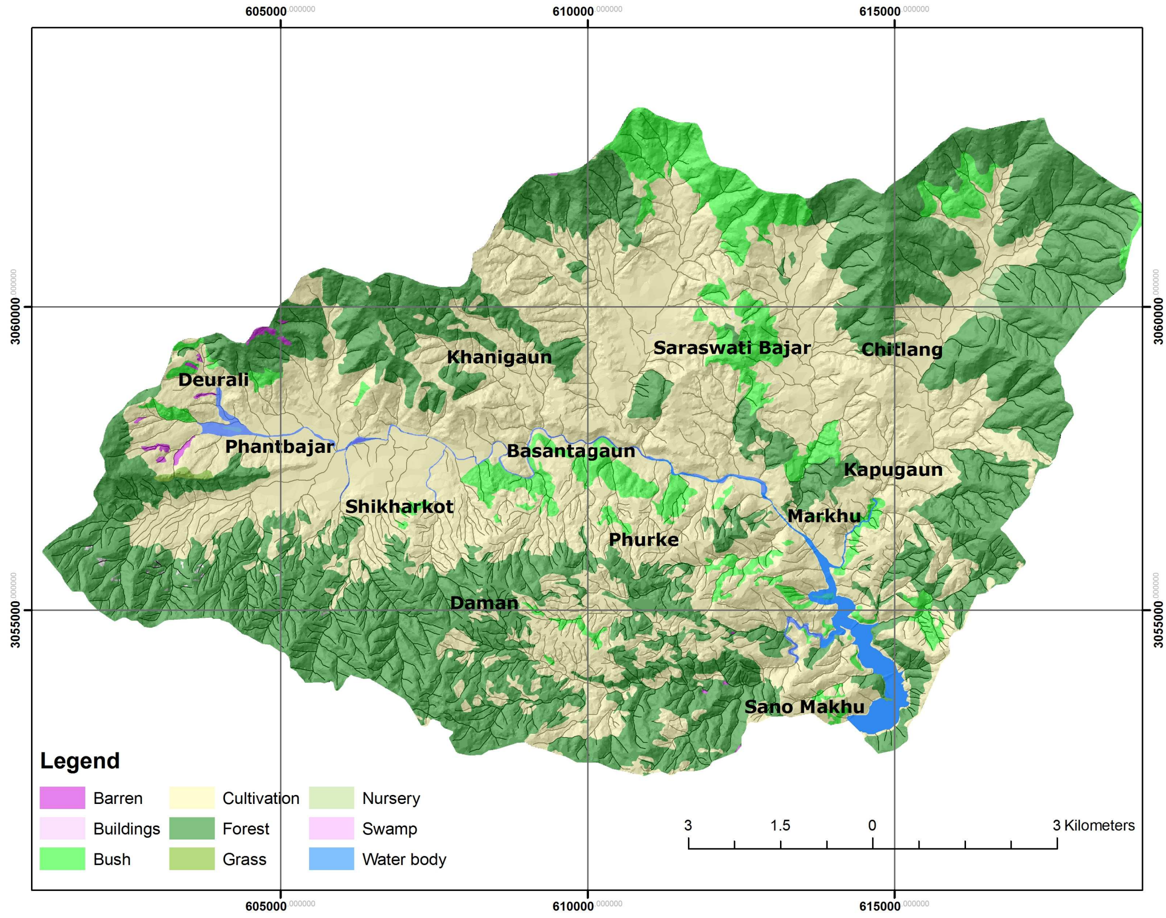


Fig 5.12: Map of Landuse classes in the study area

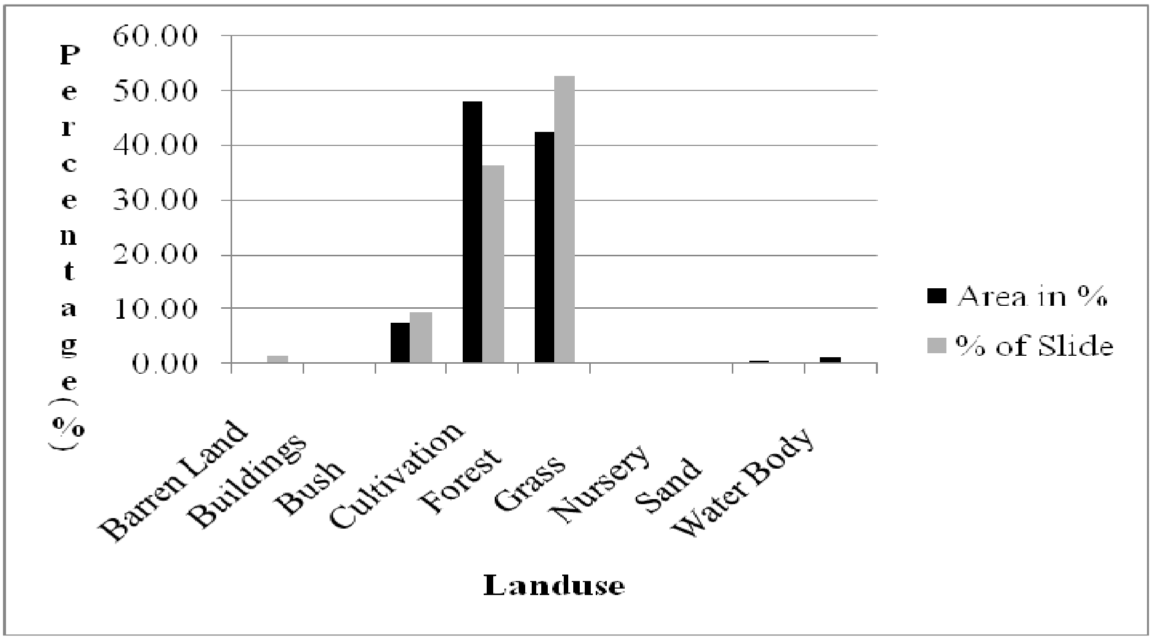


Fig 5.13: Percentage of Landuse classes with landslide occurrence

### 5.1.7 Geology

It includes the composition, fabric, texture or other attributes that influence the physical or chemical behavior of rocks and engineering soils. These attributes are very important in determining the shear strength, permeability, susceptibility to chemical and physical weathering, and other characteristics of soil and rock materials, which in turn affect slope stability (Varnes 1984). Therefore, geology has been often used for hazard mapping of landslides by many authors (Van Westen et al., 2003; Yalcin and Bulut 2008; Regmi et al., 2010). The geological map was prepared as a polygon map and then converted into raster map (Fig: 5.14). From the figure below, it can be inferred that Palung Granite occupies the largest percentage of area(29.39%) followed by Tistung Formation(22.80%).

For the landslide occurrence, largest percentage is covered by Palung Granite (37.77%) and then Kulikhani Formation (27.31%). The percentage distribution of different classes with their landslide occurrence is given below in Fig 5.15.

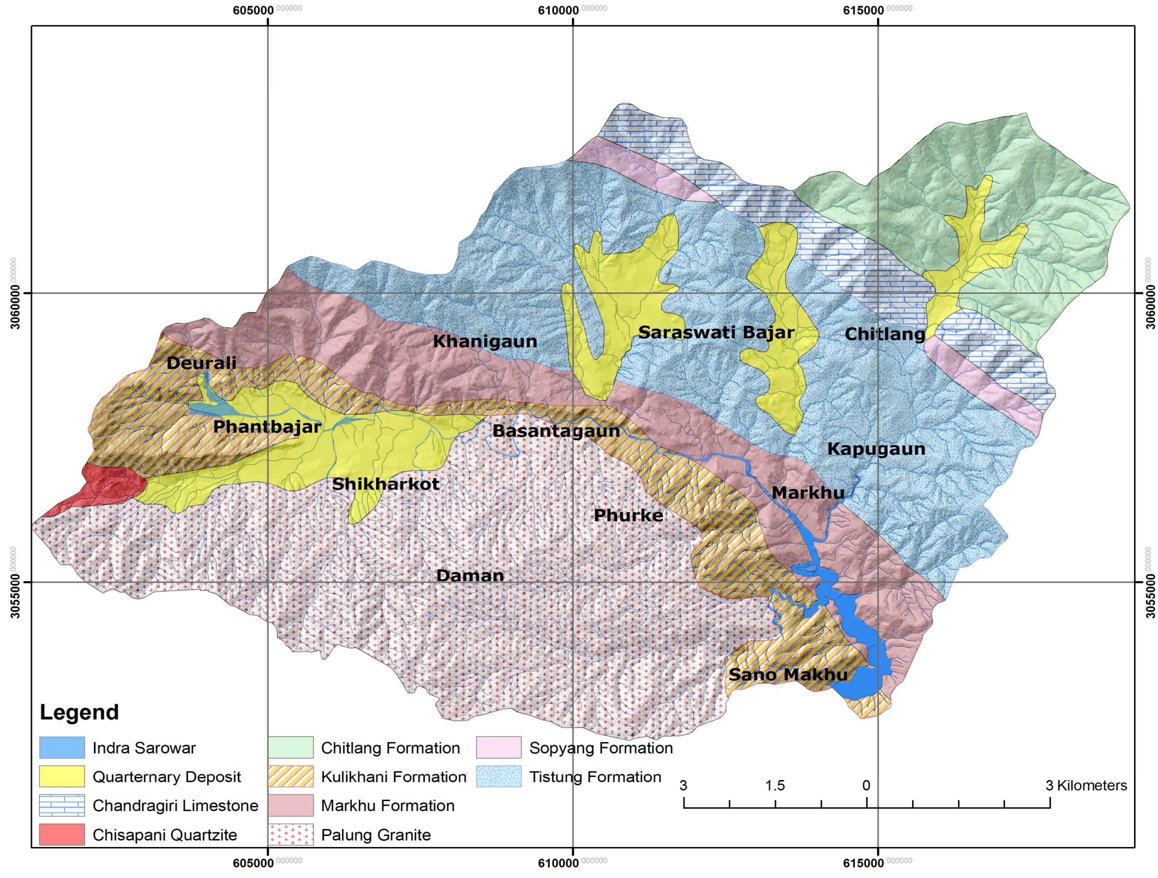


Fig 5.14: Map of Geology classes in the study area

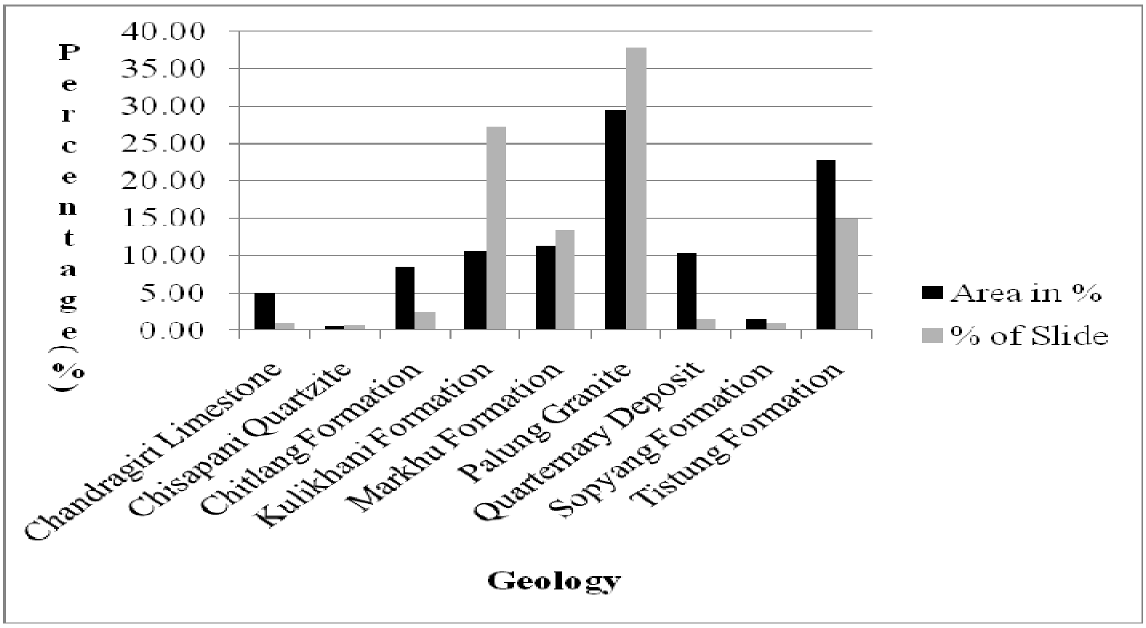


Fig 5.15: Percentage of Geological classes and landslide occurrence

## 5.2 Hazard Map Preparation

### 5.2.1 Frequency Ratio or Probability Method

Frequency Ratio or Probability Method expresses the relation between landslides occurring in an area and landslide related area can be distinguished from the relation between landslides not occurring in an area and the landslide related factors. Therefore, the greater the ratio above the unity, the stronger the relationship between landslide occurrence and the given factor's attribute, and the lower the ratio below unity, the lesser the relationship between landslide occurrence and the given factor's attribute (Lee and Pradhan, 2006).

The distribution of various data layers with their weights are given below:

Table 5.1: Weightage of each attribute class in FR Method

| SN | Parameter | Class | Frequency Ratio (Wij) |
|---|---|---|---|
| 1 | **Slope** | <15° | 0.42 |
| | | 15-25° | 0.99 |
| | | 25-35° | 1.29 |
| | | 35-45° | 1.44 |
| | | >45° | 1.39 |
| | | | |

|  |  |  |  |
|---|---|---|---|
| 2 | **Aspect** | N | 1.19 |
|  |  | NE | 1.43 |
|  |  | E | 1.37 |
|  |  | SE | 0.94 |
|  |  | S | 0.83 |
|  |  | SW | 0.58 |
|  |  | W | 0.55 |
|  |  | NW | 0.94 |
|  |  |  |  |
| 3 | **Relief** | <1700m | 1.08 |
|  |  | 1700-2000m | 0.62 |
|  |  | 2000-2300m | 1.62 |
|  |  | >2300m | 0.96 |
|  |  |  |  |
| 4 | **Int Relief** | <10m | 0.20 |
|  |  | 10-20m | 0.73 |
|  |  | 20-30m | 1.17 |
|  |  | 30-40m | 1.61 |
|  |  | 40-50m | 1.50 |
|  |  | >50m | 1.14 |
|  |  |  |  |
| 5 | **River dist** | <25m | 1.55 |
|  |  | 25-50m | 1.00 |
|  |  | 50-100m | 0.66 |
|  |  | >100m | 0.90 |
|  |  |  |  |
| 6 | **Landuse** | Barren Land | 8.48 |
|  |  | Buildings | 0.00 |
|  |  | Bush | 1.27 |
|  |  | Cultivation | 0.75 |
|  |  | Forest | 1.25 |
|  |  | Grass | 1.45 |
|  |  | Nursery | 0.00 |
|  |  | Sand | 0.35 |
|  |  | Water Body | 0.02 |
|  |  |  |  |
| 7 | **Geology** | Chandragiri Limestone | 0.21 |
|  |  | Chisapani Quartzite | 1.30 |
|  |  | Chitlang Formation | 0.29 |
|  |  | Kulikhani Formation | 2.72 |
|  |  | Markhu Formation | 1.20 |
|  |  | Palung Granite | 1.31 |
|  |  | Quarternary Deposit | 0.14 |
|  |  | Sopyang Formation | 0.59 |
|  |  | Tistung Formation | 0.66 |

From the above Table 5.1, it can be inferred that

- The relation between the slope map of study area and landslide events shows that a slope angle below 25° has a ratio <1 and for slopes above 25°, the ratio is >1, which indicates a high probability with a greater slope angle. The slope angle of the class 35-45° has the highest weightage value i.e. 1.44. This also suggests that the probability of landslides increases moreover with an increased slope angle.
- The frequency ratio from the slope aspect analysis shows that the N, NE and E facing slopes suffer from a high occurrence of landslide events than other slopes.
- The influence of a drainage system upon the landslide susceptibility is also analyzed. The relation between a landslide and drainage distance showed that when distance from a drainage line increases, the landslide occurrence probability decreases. Close to a drainage channel, there is a high frequency ratio, which means a higher susceptibility. But also at farthest distance from river the frequency ratio is high than the preceding class.
- The clout of elevation shows that highly susceptible area lies in the 2000-2300m and next is followed by <1700m.
- The frequency ratio of the internal relief is above unity for all the classes above 20m. These shows that the greater the difference of relative relief in the study area, moreover the larger is the chance of landslide. The highest value was obtained in the class of 30-40m.
- In landuse, barren land has the highest ratio above unity followed by grassland, bush and forest. The loose soil of barren land is highly susceptible to landslide.
- The geological map of the study area shows the Kulikhani formation ratio is highest (above unity) followed by Palung granite, Chisapani quartzite and Markhu formation. So in such geological setting the chances of mass movement are higher.

All weights are summed up in order to get LSI map which then is classified into three different classes as shown in Fig 5.16.

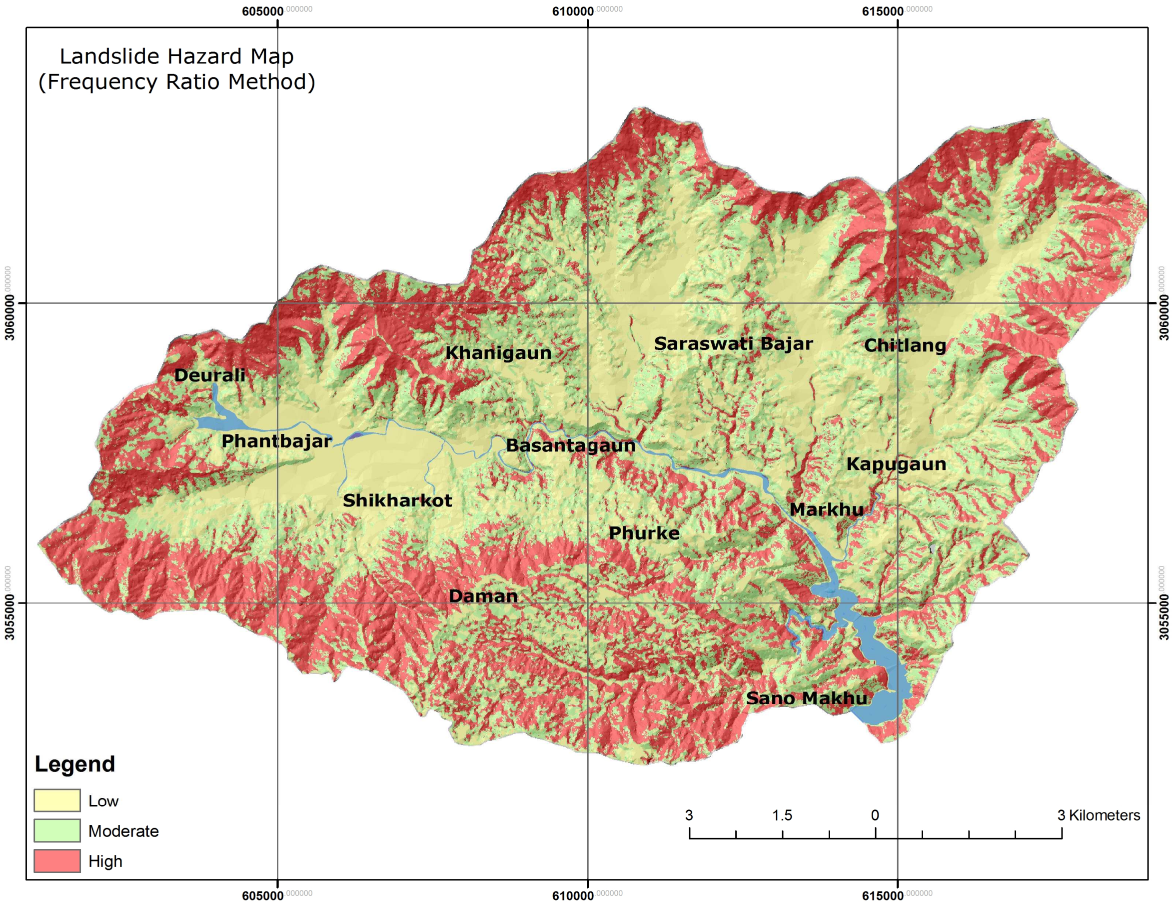


Fig 5.16: LSZ map of Kulekhani Watershed based on FR Method

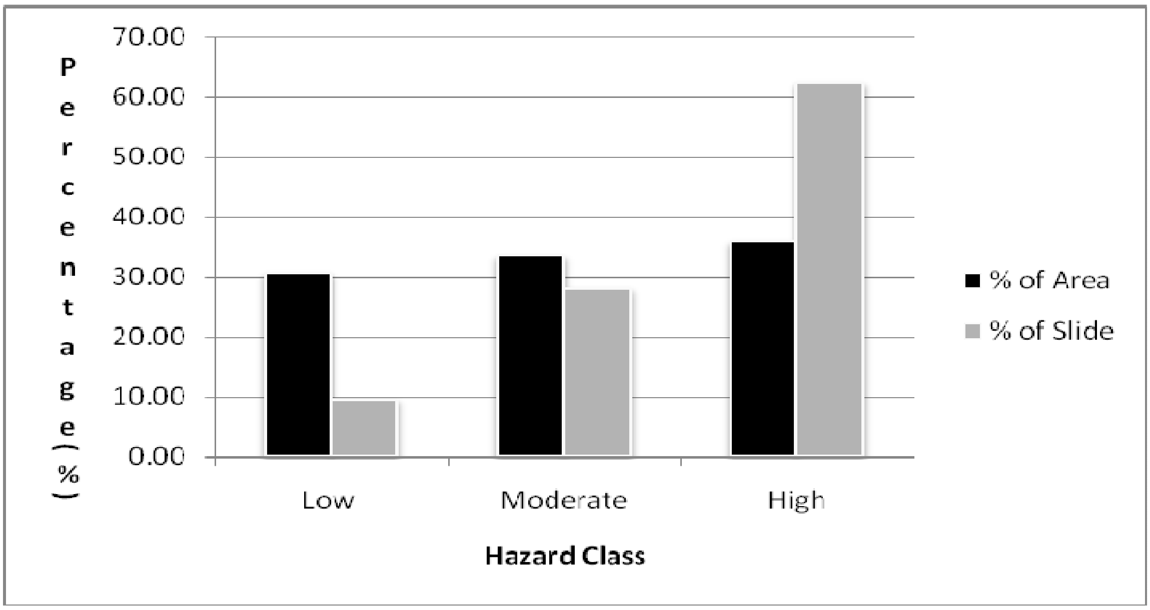


Fig 5.17: Landslide distribution w.r.t to Hazard class in FR Method

From the figure 5.16 and 5.17 of Frequency Ratio or Probability Method, it can be noted that largest percentage of hazard falls under high hazard class (35.93%) followed by moderate hazard (33.45%) and low hazard class (30.62%). Also percentage of landslide falling under three categories are 62.41%, 28.01% and 9.57% respectively.

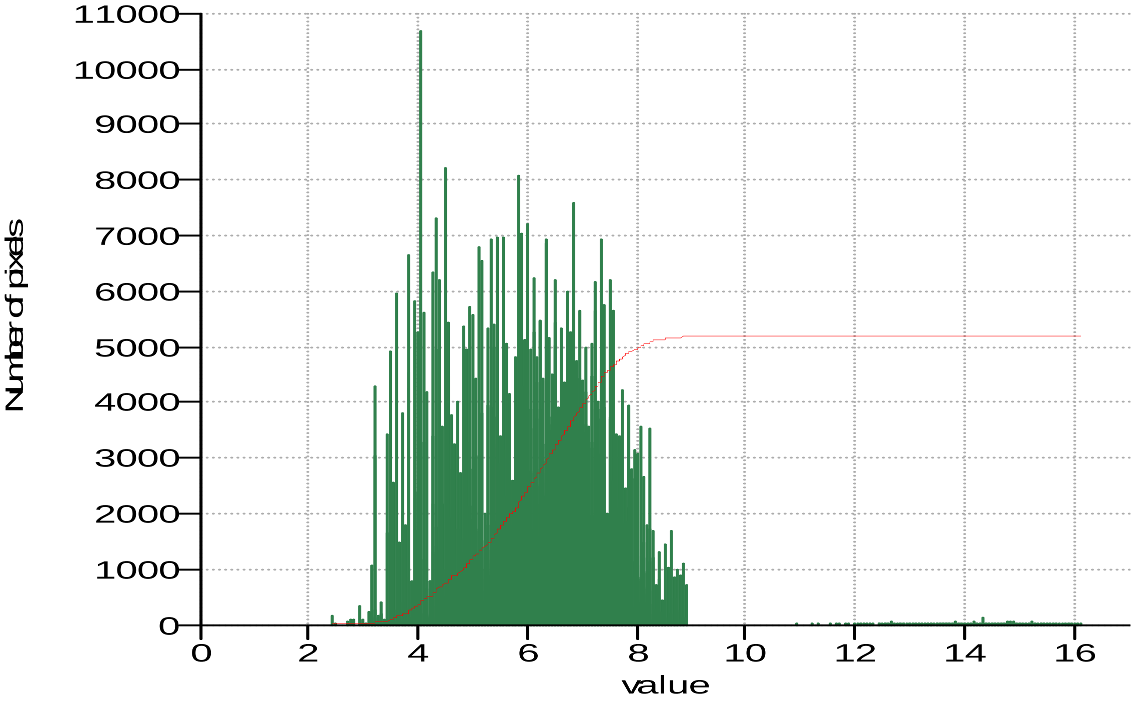


Fig 5.18: Frequency Ratio Curve

### 5.2.2 Statistical Index Method

Statistical Index Method is based on statistical correlation of landslide inventory map with attributes of different parameter map. The $W_{ij}$ value is assigned to those that have landslide occerence and those having no landslide will be assigned as Zero. It also means that parameter having no landslide has no correlation with landslide inventory.

The distribution of various data layers with their weight values are shown in the table below:

Table 5.2: Weightage of each attribute class in SIM

| SN | Parameter | Class | Statistical Index Method(Wij) |
|---|---|---|---:|
| 1 | **Slope** | <15° | -0.86 |
| | | 15-25° | -0.01 |
| | | 25-35° | 0.25 |
| | | 35-45° | 0.36 |
| | | >45° | 0.32 |
| | | | |
| 2 | **Aspect** | N | 0.17 |
| | | NE | 0.35 |
| | | E | 0.31 |
| | | SE | -0.06 |
| | | S | -0.18 |
| | | SW | -0.53 |
| | | W | -0.59 |
| | | NW | -0.06 |
| | | | |
| 3 | **Relief** | <1700m | 0.08 |
| | | 1700-2000m | -0.48 |
| | | 2000-2300m | 0.47 |
| | | >2300m | -0.04 |
| | | | |
| 4 | **Int Relief** | <10m | -1.58 |
| | | 10-20m | -0.31 |
| | | 20-30m | 0.16 |
| | | 30-40m | 0.46 |
| | | 40-50m | 0.39 |
| | | >50m | 0.13 |
| | | | |
| 5 | **River dist** | <25m | 0.43 |
| | | 25-50m | 0.00 |
| | | 50-100m | -0.41 |
| | | >100m | -0.10 |

| | | | |
|---|---|---|---|
| | | | |
| 6 | **Landuse** | Barren Land | 2.00 |
| | | Buildings | 0.00 |
| | | Bush | 0.23 |
| | | Cultivation | -0.28 |
| | | Forest | 0.22 |
| | | Grass | 0.36 |
| | | Nursery | 0.00 |
| | | Sand | -1.03 |
| | | Water Body | -3.98 |
| | | | |
| 7 | **Geology** | Chandragiri Limestone | -1.57 |
| | | Chisapani Quartzite | 0.26 |
| | | Chitlang Formation | -1.21 |
| | | Kulikhani Formation | 0.97 |
| | | Markhu Formation | 0.18 |
| | | Palung Granite | 0.26 |
| | | Quarternary Deposit | -1.95 |
| | | Sopyang Formation | -0.52 |
| | | Tistung Formation | -0.41 |

From the above table 5.2, it can be noted that:

- The relation between the slope map and the landslide events shows that the more steeper the slope more chances of landslide. But at higher slope angle i.e. >45°, less landsliding probability occur. Its probably due to that loose earth material do not hold firm and were already slipped in ancient time.
- In relation to aspect, N, NE and E facing slope has higher susceptibility than other side facing slope.
- The influence of elevation is also prominent in the relief of 2000-2300m. High landsliding probability can be inferred from the above mentioned slope.
- The weightage value of the internal relief is positive for all the classes above 20m. These shows that the greater the difference of relative relief in the study area, moreover the larger is the chance of landslide. The highest value was obtained in the class of 30-40m.

- The influence of a drainage system upon the landslide susceptibility is also analyzed. The relation between a landslide and drainage distance showed that when distance from a drainage line increases, the landslide occurrence probability decreases. Close to a drainage channel, there is a high weightage value which means a higher susceptibility.
- In landuse, barren land has the highest ratio above unity followed by grassland, bush and forest. The loose soil of barren land is highly susceptible to landslide.
- In the geological map, higher weights are found in Kulikhani formation, Palung granite and Chisapani quartzite. This may reveal the fact that they are more susceptible to landslide than other geological formation.

All weights are summed up in order to get LSI map which then is classified into three different classes as shown in Fig 5.19.

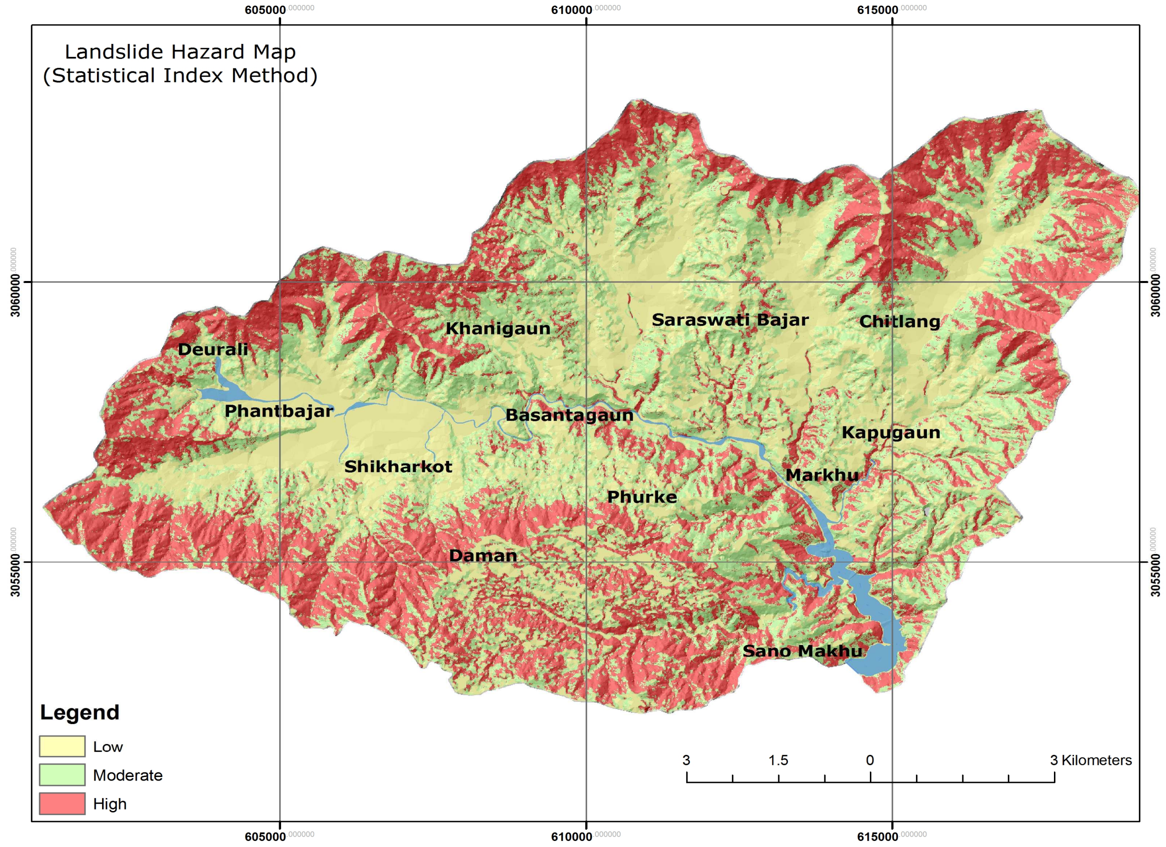


Fig 5.19: LSZ map of Kulekhani Watershed based on SIM

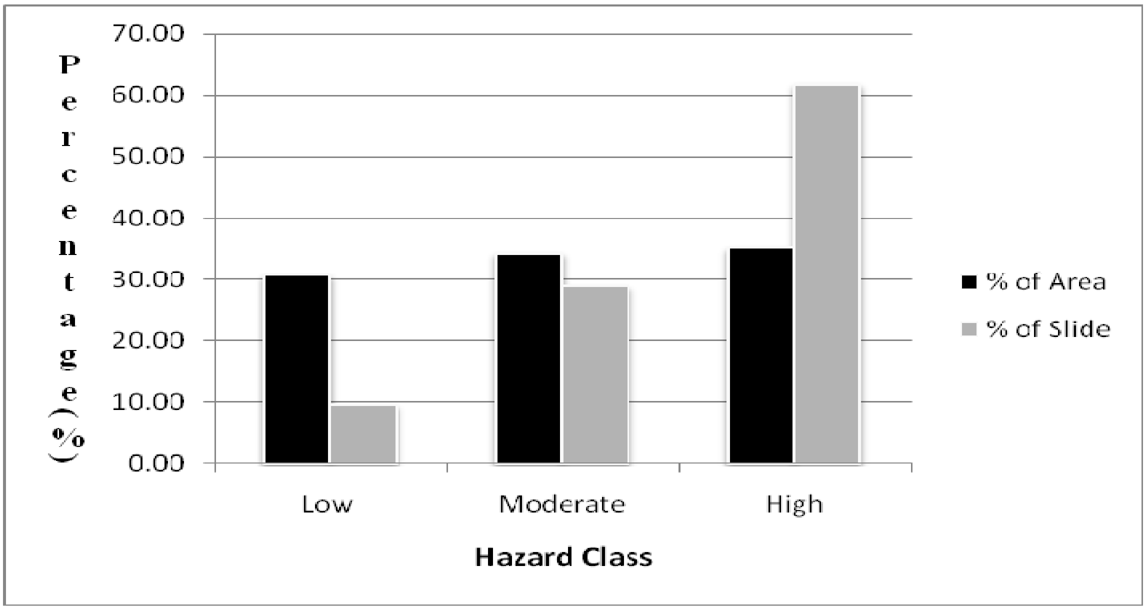


Fig 5.20: Fig: Landslide distribution w.r.t to Hazard class in SIM

From the figure 5.19 and 5.20 of Statistical Index Method, 35.12% area falls under high hazard class, 34.26% and 30.62% falls under moderate hazard and low hazard class respectively. Similarly, out of total landslide, 61.72%, 28.77% and 9.52% falls under high, moderate and low hazard class.

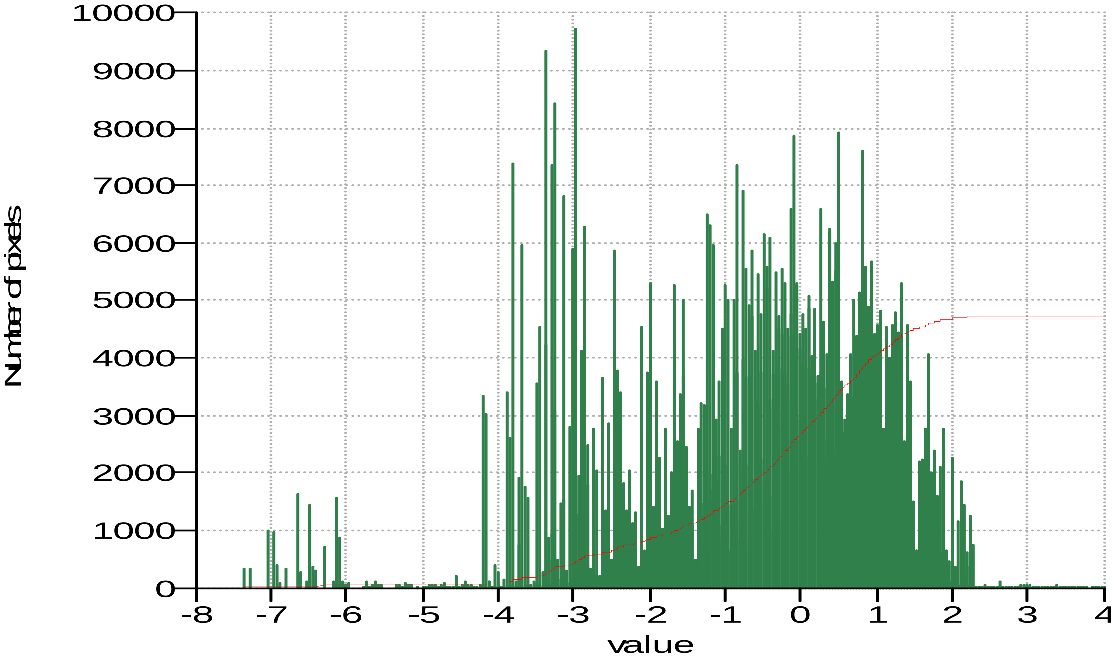


Fig 5.21: Statistical Index Method Curve

### 5.2.3 Landslide Susceptibility Analysis

Landslide susceptibility analysis is a simple and useful bivariate method to determine the importance of different variables for landslide occurrence. To evaluate the influence of each variable, weighting factors are determined, which compare the calculated density with the overall density in the area (Suzen and Doyuran, 2004).

The resulting weights are given in the table below:

Table 5.3: Weightage of each attribute class in LSA

| SN | Parameter | Class | Landslide Susceptibility Analysis(Wij) |
|---|---|---|---|
| 1 | **Slope** | <15° | -11.71 |
| | | 15-25° | -0.22 |
| | | 25-35° | 5.67 |
| | | 35-45° | 8.72 |
| | | >45° | 7.80 |
| | | | |
| 2 | **Aspect** | N | 3.72 |
| | | NE | 8.58 |
| | | E | 7.30 |
| | | SE | -1.18 |
| | | S | -3.40 |
| | | SW | -8.40 |
| | | W | -9.08 |
| | | NW | -1.13 |
| | | | |
| 3 | **Relief** | <1700m | 1.63 |
| | | 1700-2000m | -7.73 |
| | | 2000-2300m | 12.31 |
| | | >2300m | -0.73 |
| | | | |
| 4 | **Int Relief** | <10m | -16.19 |
| | | 10-20m | -5.45 |
| | | 20-30m | 3.42 |
| | | 30-40m | 11.95 |
| | | 40-50m | 9.82 |
| | | >50m | 2.87 |
| | | | |

|  |  |  |  |
|---|---|---|---|
| 5 | **River dist** | <25m | 10.88 |
|  |  | 25-50m | -0.07 |
|  |  | 50-100m | -6.81 |
|  |  | >100m | -2.02 |
|  |  |  |  |
| 6 | **Landuse** | Barren Land | 129.48 |
|  |  | Buildings | -20.37 |
|  |  | Bush | 5.37 |
|  |  | Cultivation | -4.99 |
|  |  | Forest | 4.94 |
|  |  | Grass | 8.83 |
|  |  | Nursery | -20.37 |
|  |  | Sand | -13.08 |
|  |  | Water Body | -19.99 |
|  |  |  |  |
| 7 | **Geology** | Chandragiri Limestone | -16.11 |
|  |  | Chisapani Quartzite | 5.93 |
|  |  | Chitlang Formation | -14.31 |
|  |  | Kulikhani Formation | 33.18 |
|  |  | Markhu Formation | 3.91 |
|  |  | Palung Granite | 6.12 |
|  |  | Quarternary Deposit | -17.46 |
|  |  | Sopyang Formation | -8.29 |
|  |  | Tistung Formation | -6.84 |

From Table 5.3, following things can be noted down:

- The relation between the slope map and the landslide events shows that the more steeper the slope more chances of landslide. But at higher slope angle i.e. >45°, less landsliding probability occur.
- Aspect also plays an important relation to landslide. From the value mentioned above N, NE and E facing slope has higher susceptibility than other side facing slope.
- The influence of elevation is also prominent in the relief of 2000-2300m.
- The weight value of the internal relief is positive for all the classes above 20m. These shows that the greater the difference of relative relief in the study area, moreover the larger is the chance of landslide. The highest value was obtained in the class of 30-40m.

- The influence of a drainage system upon the landslide susceptibility is also analyzed. The relation between a landslide and drainage distance showed that when distance from a drainage line increases, the landslide occurrence probability decreases. Close to a drainage channel, there is a high weightage value which means a higher susceptibility. The farthest one also has less susceptibility than its preceding one.
- In landuse, barren land has the highest ratio above unity followed by grassland, bush and forest. The loose soil of barren land is highly susceptible to landslide.
- The geological map of the study area shows that Kulikhani formation has the highest weightage and so is its susceptibility is more than other lithological settings.

All weights are summed up in order to get LSI map which then is classified into three different classes as shown in Fig 5.22

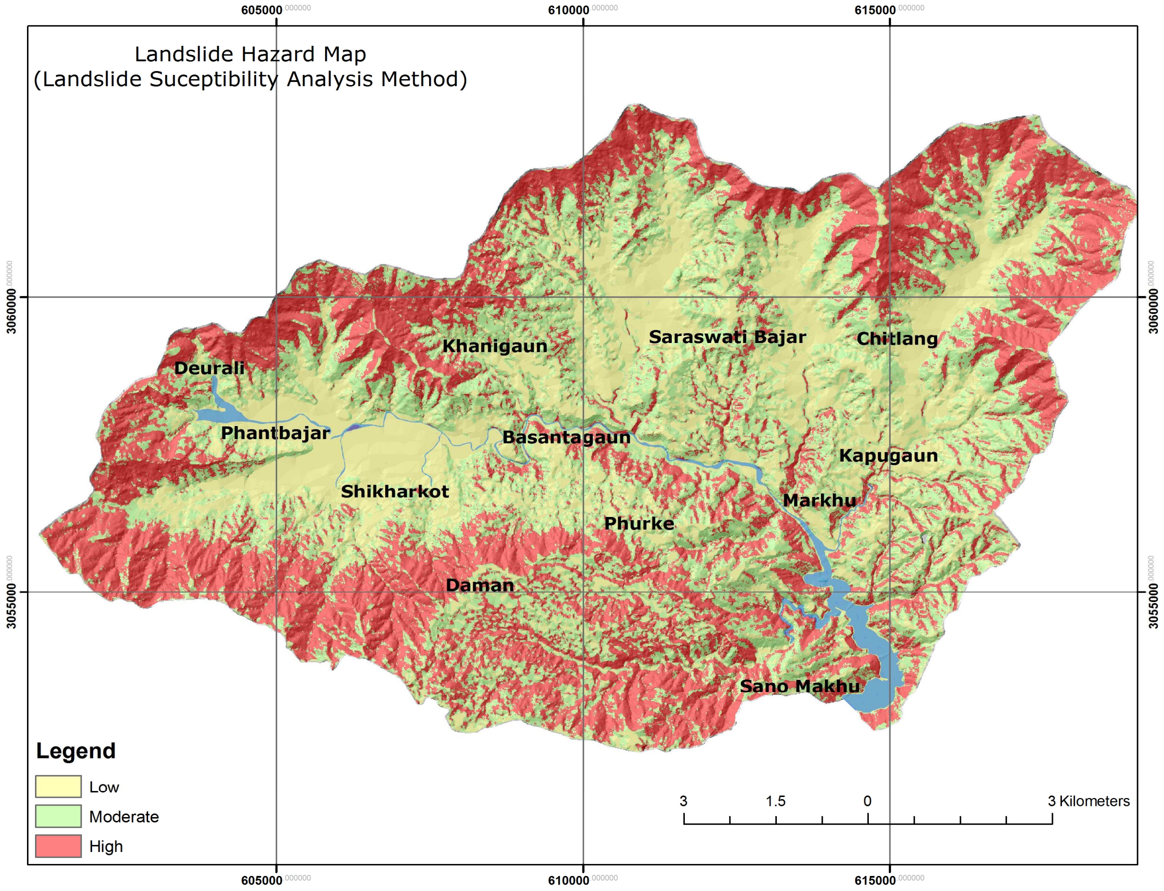


Fig 5.22: LSZ map of Kulekhani Watershed based on LSA

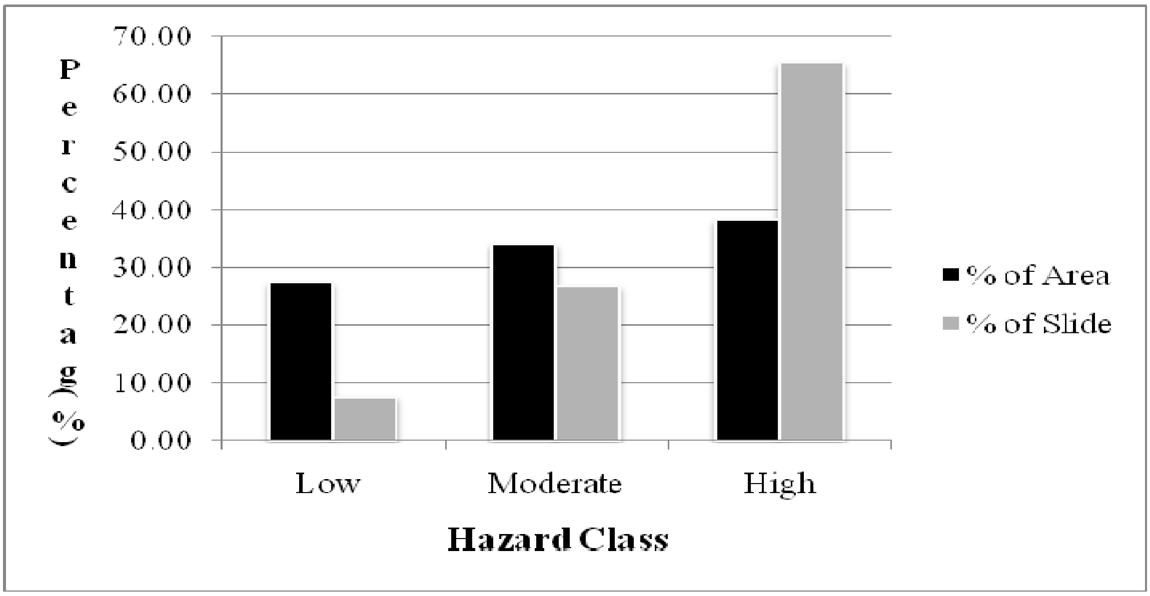


Fig 5.23: Landslide distribution w.r.t Hazard Class in LSA

The hazard zonation map (Fig: 5.22) and its corresponding graph (Fig 5.23) under the Landslide Susceptibility Analysis depicts the area of high, moderate and low to be 38.35%, 34.12% and 27.54% respectively. In the corresponding hazard areas, the percentage of landslide are found to be 65.61%, 26.82% and 7.58% respectively.

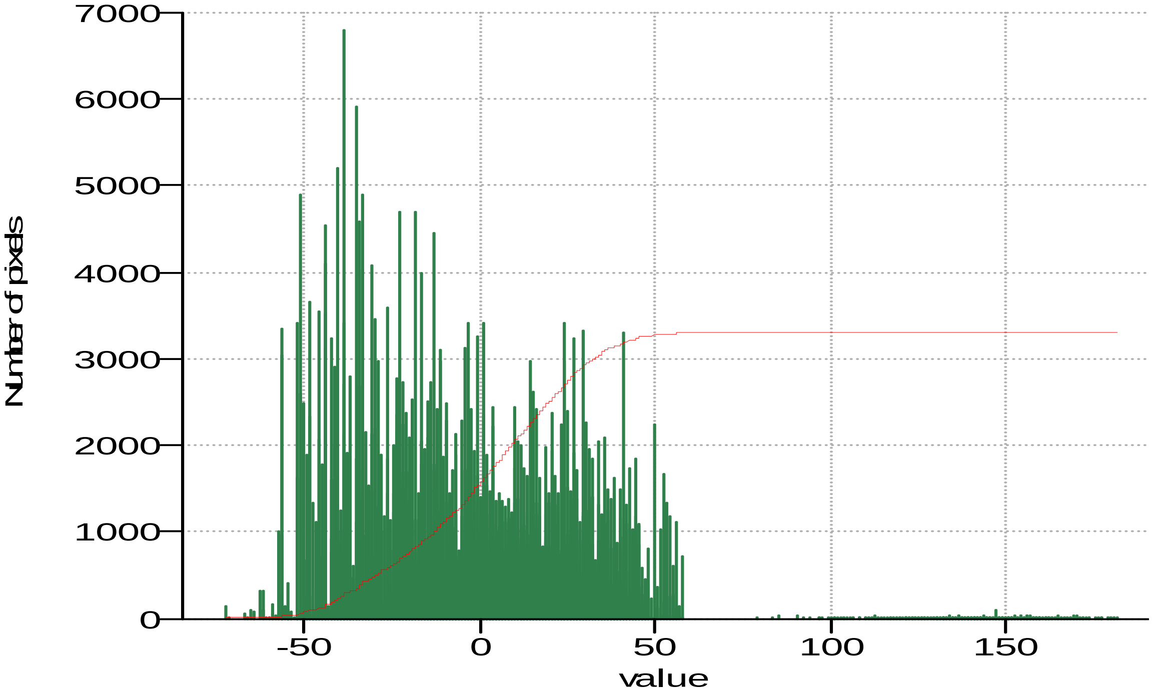


Fig 5.24: Landslide Susceptibility Analysis Curve

### 5.2.4 Weight of Evidence Modelling

WOE model is fundamentally based on the calculation of positive and negative weights ($W^+$ and $W^-$), the magnitude of which depends on the measured association between the response variable (the landslides) and the predictor variables (causative factors).

The factor maps combined with landslide occurrence map enable to calculate the overall weights are given in the table below:

Table 5.4: Weightage of each attribute class in WOE Modelling

| SN | Parameter | Class | Weight Of Evidence C. Wt |
|---|---|---|---|
| 1 | **Slope** | <15° | -1.07 |
| | | 15-25° | -0.02 |
| | | 25-35° | 0.35 |
| | | 35-45° | 0.43 |
| | | >45° | 0.36 |
| | | | |
| 2 | **Aspect** | N | 0.20 |
| | | NE | 0.41 |
| | | E | 0.39 |
| | | SE | -0.07 |
| | | S | -0.22 |
| | | SW | -0.58 |
| | | W | -0.67 |
| | | NW | -0.07 |
| | | | |
| 3 | **Relief** | <1700m | 0.09 |
| | | 1700-2000m | -0.82 |
| | | 2000-2300m | 0.79 |
| | | >2300m | -0.04 |
| | | | |
| 4 | **Int Relief** | <10m | -1.75 |
| | | 10-20m | -0.42 |
| | | 20-30m | 0.22 |
| | | 30-40m | 0.62 |
| | | 40-50m | 0.43 |
| | | >50m | 0.13 |
| | | | |
| 5 | | <25m | 0.62 |

| | | | |
|---|---|---|---|
| | **River dist** | 25-50m | -0.01 |
| | | 50-100m | -0.55 |
| | | >100m | -0.15 |
| | | | |
| 6 | **Landuse** | Barren Land | 2.15 |
| | | Buildings | 0.00 |
| | | Bush | 0.26 |
| | | Cultivation | -0.50 |
| | | Forest | 0.42 |
| | | Grass | 0.37 |
| | | Nursery | 0.00 |
| | | Sand | -1.05 |
| | | Water Body | -4.01 |
| | | | |
| 7 | **Geology** | Chandragiri Limestone | -1.63 |
| | | Chisapani Quartzite | 0.26 |
| | | Chitlang Formation | -1.29 |
| | | Kulikhani Formation | 1.21 |
| | | Markhu Formation | 0.20 |
| | | Palung Granite | 0.40 |
| | | Quarternary Deposit | -2.06 |
| | | Sopyang Formation | -0.54 |
| | | Tistung Formation | -0.51 |

The above table 5.4 indicates:

- Slope larger than 25° have positive weight value so they have proportional or significant relation with the landslide occurrence.
- For aspect factor, the direction of slope which has significant impact is found to be N, NE, E.
- The elevation of the class 2000-2300m has found to be impacting on the occurrence landslides.
- Internal relief higher than 20m have positive values, so in connection they have important part in landsliding phenomenon.
- In landuse barren land has the highest impact on the landslide occurrence and so followed by grass, bush and forest.

- The relation between a landslide and drainage distance showed that when distance from a drainage line increases, the landslide occurrence probability decreases.
- The geological map of the study area shows that Kulikhani formation has the highest weightage and so is its susceptibility is more and is highly vulnerable to landslide. The least affected is Quarternary deposit.

All weights are summed up in order to get LSI map which then is classified into three different classes as shown in Fig 5.25

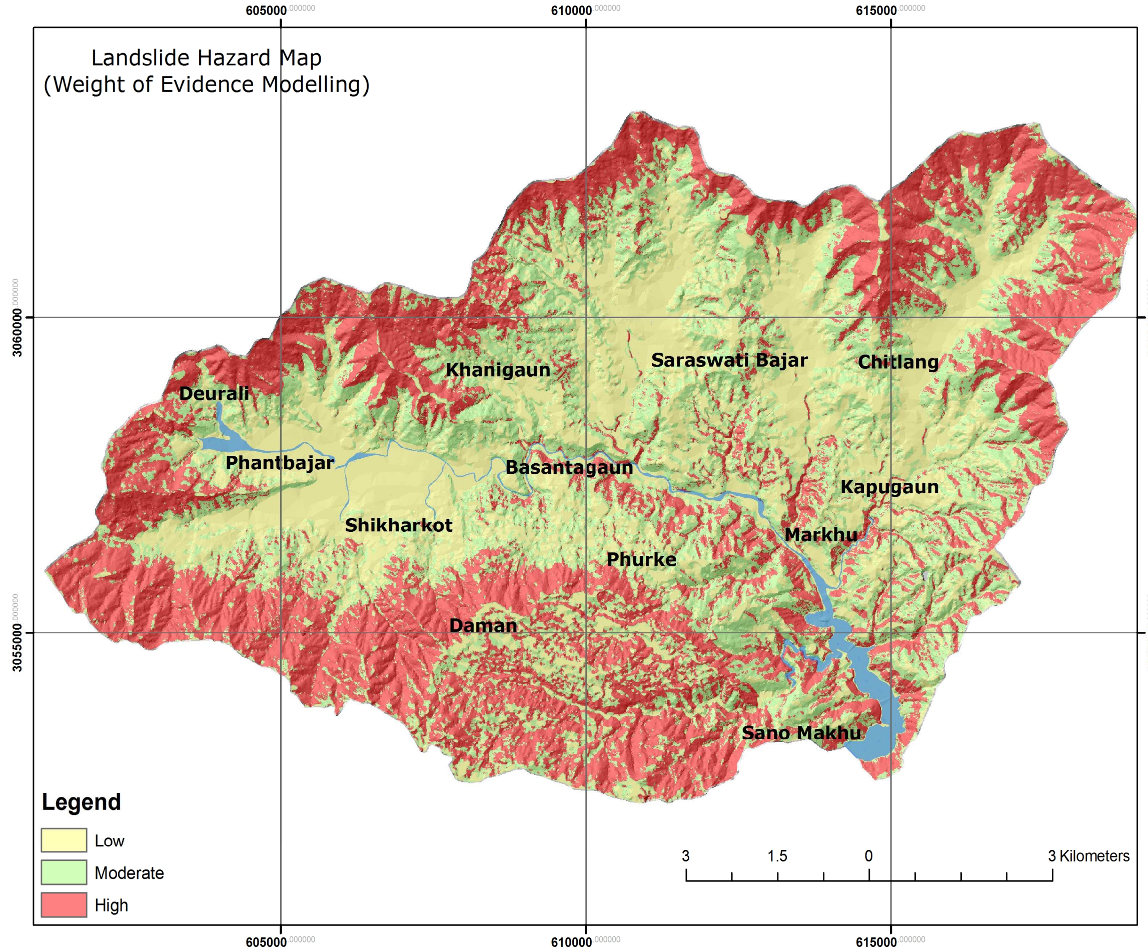


Fig 5.25: LSZ map of Kulekhani Watershed based on WOE Modelling

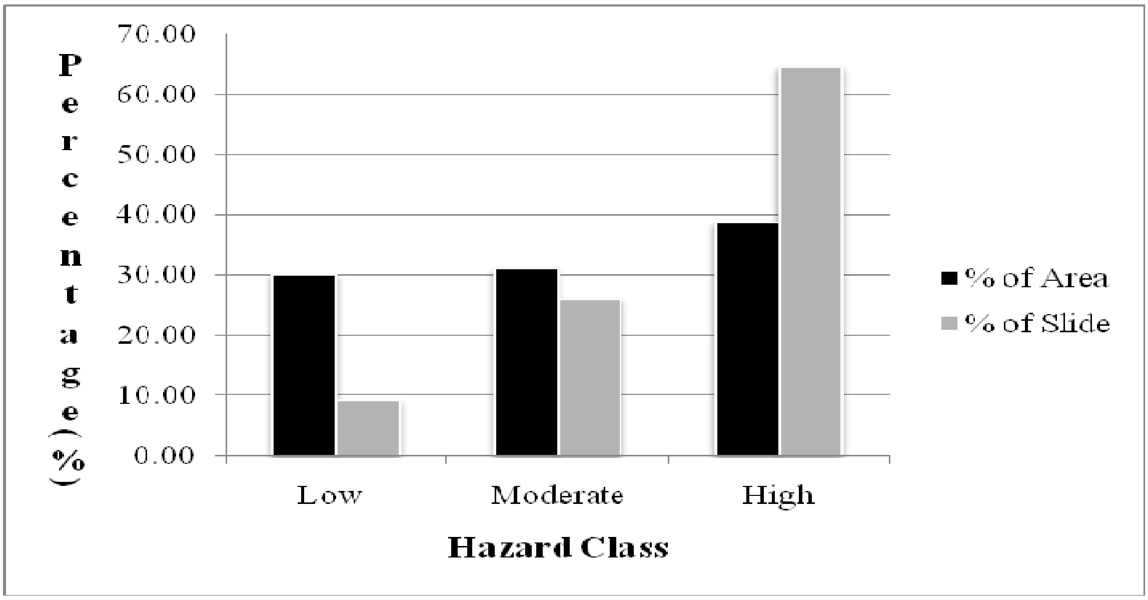


Fig 5.26: Landslide distribution w.r.t Hazard Class in WOE Modelling

In classifying the hazard area of Kulekhani watershed through Weight of Evidence Modelling, 38.75% area falls under high hazard, 31.14% under moderate hazard and 30.11% in low hazard class. Similarly, the landslide occurrence in those corresponding area are found to be 64.63%, 26.13% and 9.23% respectively.

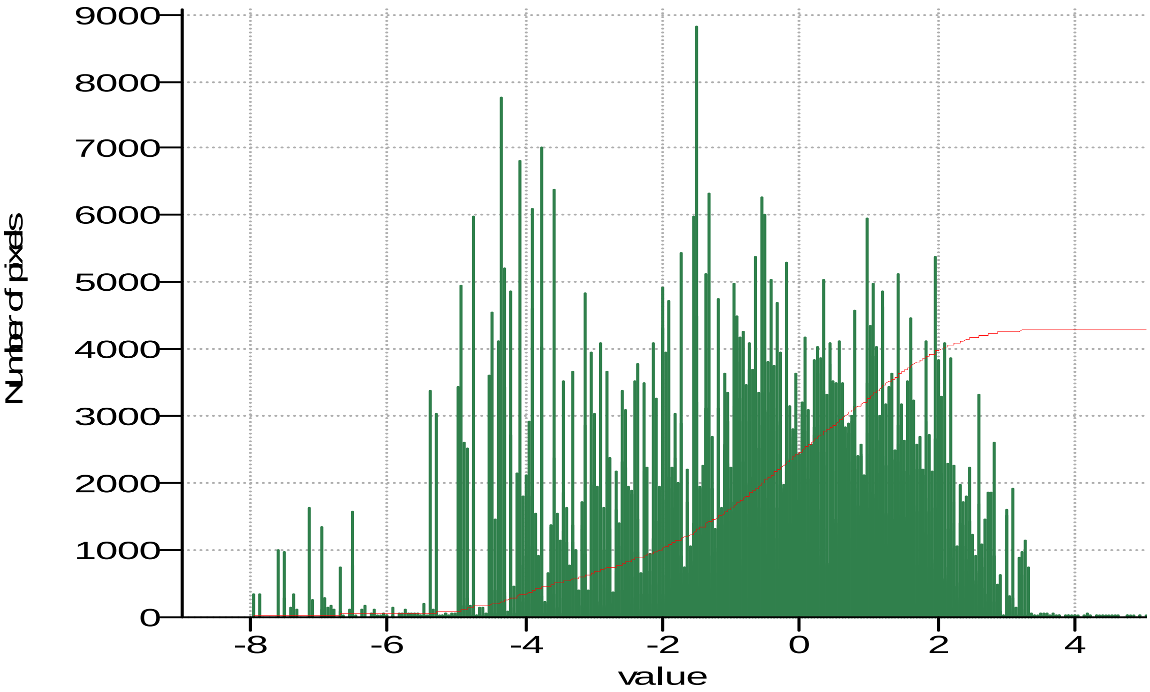


Fig 5.27: Weight of Evidence Modelling Curve

### 5.2.5 Certainty Factor

Certainty factor is a number to measure the researcher’s opinion. The range of the certainty factor is [-1, +1]. Positive value indicates an increasing certainty in landslide occurrence, while negative value corresponds to a decreasing certainty in landslide occurrence. A value close to zero ‘0’ is difficult to assess about the certainty of landslide occurrence.

The factor maps combined with landslide occurrence map enable to calculate the overall weights are given in the table below:

Table 5.5: Weightage of each attribute class in CF Method

| SN | Parameter | Class | Certainty Factor (CFij) |
|---|---|---|---:|
| 1 | **Slope** | <15° | -0.58 |
|  |  | 15-25° | -0.01 |
|  |  | 25-35° | 0.22 |
|  |  | 35-45° | 0.31 |
|  |  | >45° | 0.28 |
|  |  |  |  |
| 2 | **Aspect** | N | 0.16 |
|  |  | NE | 0.30 |
|  |  | E | 0.27 |
|  |  | SE | -0.06 |
|  |  | S | -0.17 |
|  |  | SW | -0.42 |
|  |  | W | -0.45 |
|  |  | NW | -0.06 |
|  |  |  |  |
| 3 | **Relief** | <1700m | 0.08 |
|  |  | 1700-2000m | -0.38 |
|  |  | 2000-2300m | 0.38 |
|  |  | >2300m | -0.04 |
|  |  |  |  |
| 4 | **Int Relief** | <10m | -0.80 |
|  |  | 10-20m | -0.27 |
|  |  | 20-30m | 0.15 |
|  |  | 30-40m | 0.38 |
|  |  | 40-50m | 0.33 |
|  |  | >50m | 0.13 |
|  |  |  |  |

| | | | |
|---|---|---|---|
| 5 | **River dist** | <25m | 0.36 |
| | | 25-50m | 0.00 |
| | | 50-100m | -0.34 |
| | | >100m | -0.10 |
| | | | |
| 6 | **Landuse** | Barren Land | 0.88 |
| | | Buildings | -1.00 |
| | | Bush | 0.21 |
| | | Cultivation | -0.25 |
| | | Forest | 0.20 |
| | | Grass | 0.31 |
| | | Nursery | -1.00 |
| | | Sand | -0.65 |
| | | Water Body | -0.98 |
| | | | |
| **7** | **Geology** | Chandragiri Limestone | -0.79 |
| | | Chisapani Quartzite | 0.23 |
| | | Chitlang Formation | -0.71 |
| | | Kulikhani Formation | 0.63 |
| | | Markhu Formation | 0.16 |
| | | Palung Granite | 0.24 |
| | | Quarternary Deposit | -0.86 |
| | | Sopyang Formation | -0.41 |
| | | Tistung Formation | -0.34 |

From the above table 5.5 some conclusions can be infered:

- The slope class 35-45° has the highest Certainty Factor value (0.31), so it is most prone to landslide. The ngative value indicate that those slope classes are unlikely to fail.
- The positive value of N, NE, E indicates that these aspect classes are more vulnerable than other facing slopes.
- Elevation of the class 2000-2300m has the largest value i.e. 0.38, so it can be said that this class is most vulnerable and landslide phenomena can highly occur.
- Internal relief of class higher than 20m has positive value, so from the value it can be concluded that internal relief >20m is more susceptible than its preceding class.

- Drainage distance also plays an important role in the occurrence of landslide. From the above table, distance <25m has the significant value than other class, so it is most prone to landslide.
- In landuse, barren land favour for the landslide phenomena. Other classes do not have much impact as that of barren land.
- In the same way as of other method of analysis, the geological formation of the study area seems to resemble. The Kulikhani formation has the highest weightage value and is more vulnerable and Quarternary deposity the least.

All weights are summed up in order to get LSI map which then is classified into three different classes as shown in Fig 5.28

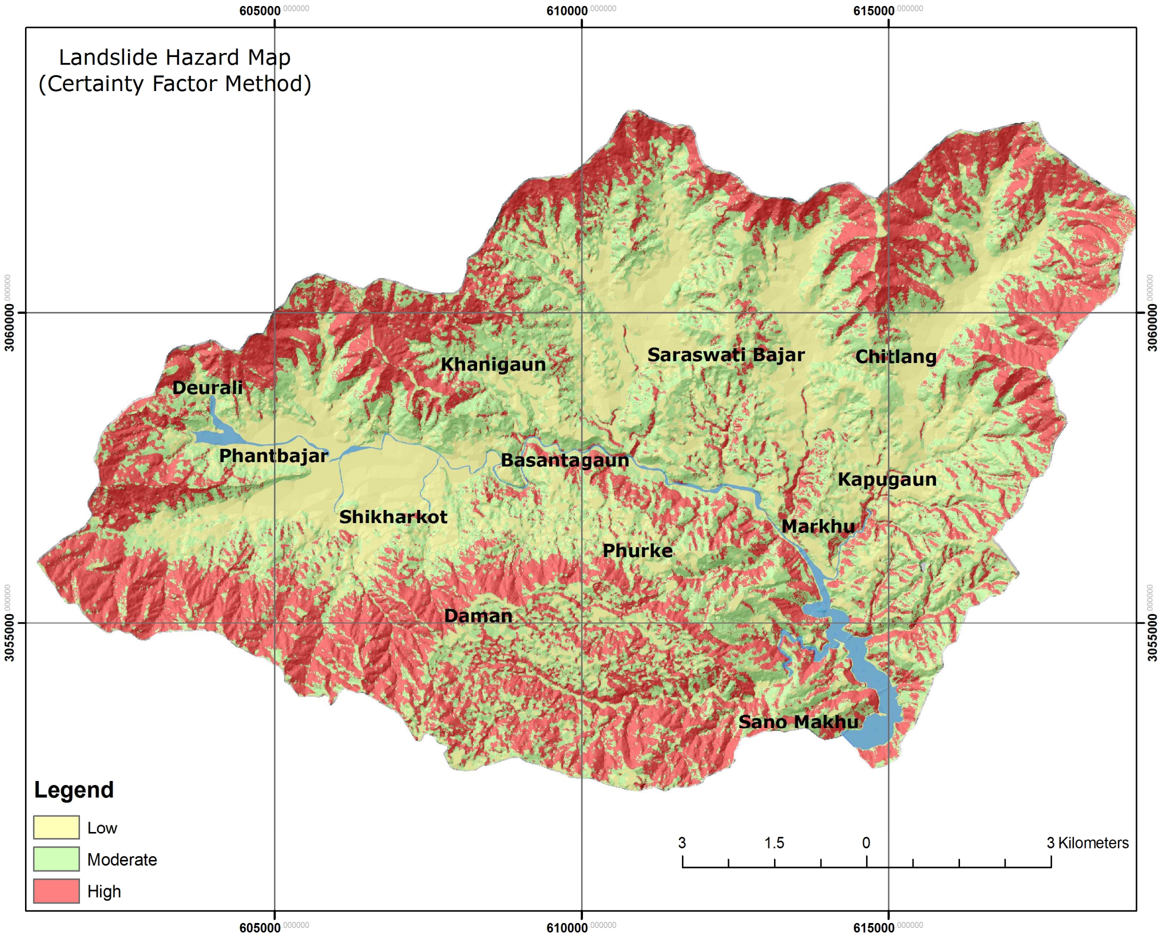


Fig 5.28: LSZ map of Kulekhani Watershed based on CF Method

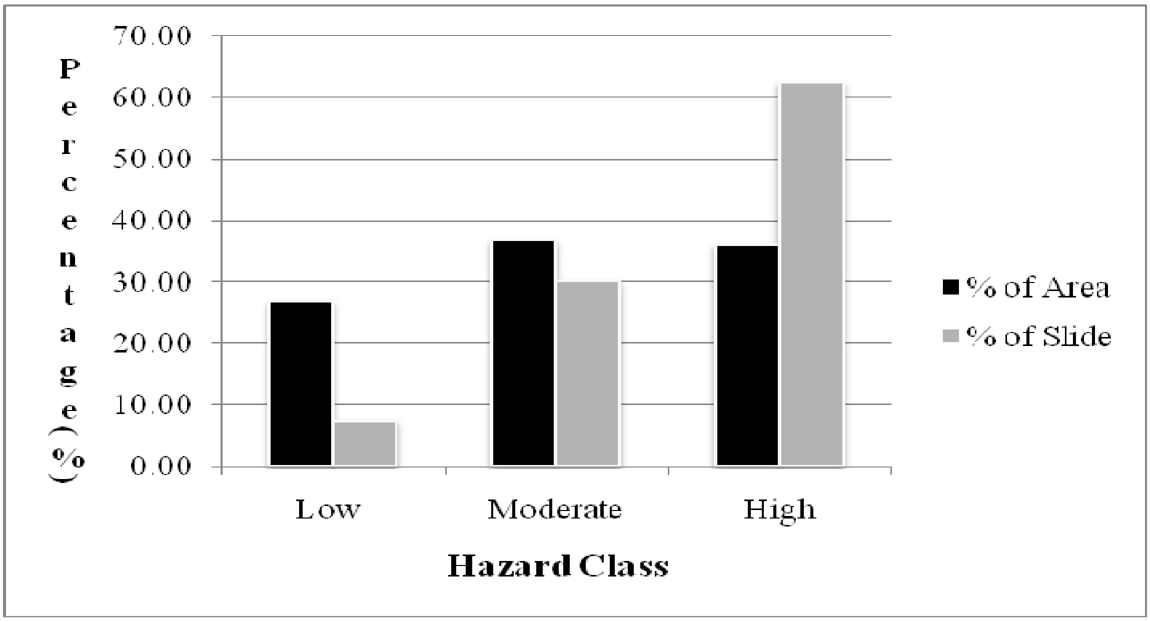


Fig 5.29: Landslide distribution w.r.t Hazard Class in CF Method

Through Certainty Factor method as depicted in Figure 5.28 and 5.29 found that 36.20%, 36.85% and 26.95% falls under high hazard, moderate hazard and low hazard susceptibility class. Out of which, 62.60% landslide lies in high hazard, 30.08% lies in moderate hazard and 7.32% under low hazard susceptibility class.

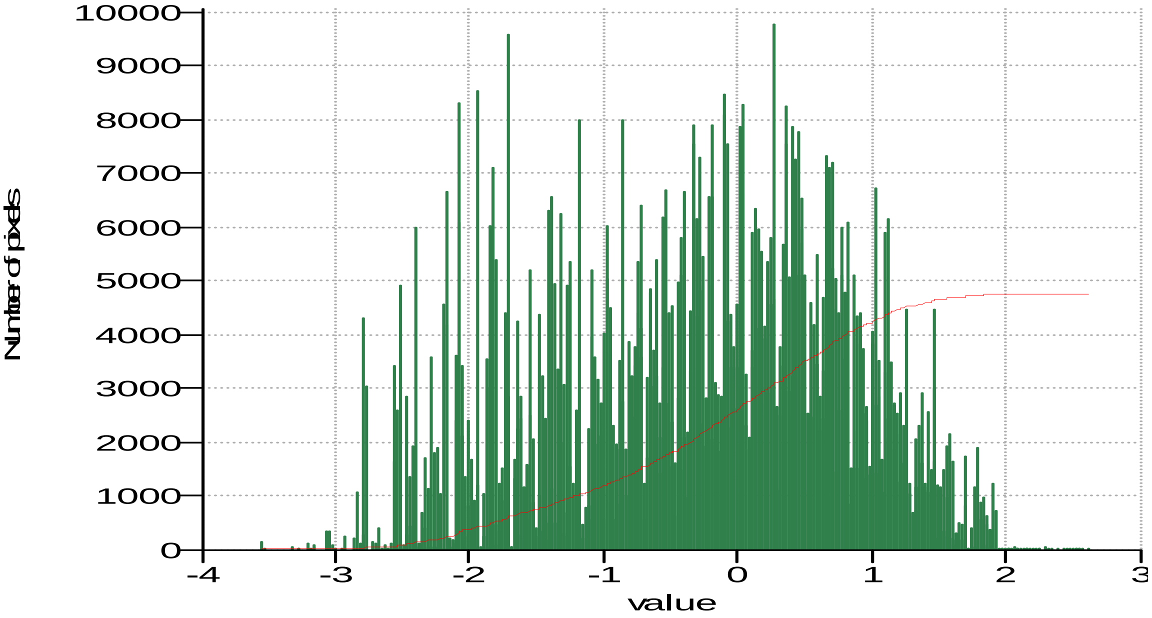


Fig 5.30: Certainty Factor Curve

# Chapter 6: Discussion

Landslide, like other natural hazards such as flood, earthquake and avalanche is often difficult to predict. But in general, to predict landslides, it is necessary to assume that landslide occurrence is determined by landslide-related factors, and future landslide will occur under the same conditions as past landslides.

Above result depicted that agricultural land and forest are most vulnerable than other land use type among five methods applied to identify the hazard map of the study area. Geological location of Forest i.e. most of the forested area lies in north side facing slope and traditional farming practice might be the reason behind the landslide occurrence. Also, forest has unusually higher percentages of landslides; this may due to the account that the shallow root penetration might be the cause as it could not hold the soil properly. Deforestation due to human activities is making area more susceptible towards landslide. Similarly other variables which might influence on landslide are slope factor where North, North East and East facing slopes are most likely to have landslide. This may be due to the fact that the difference in the amount of energy received as sunlight. In the Northern Hemisphere, east, south and west facing slopes receive generally more sunlight than north facing one. This leads to humid climate at the southern side while at the northern part arid climate prevails which may make the area fragile. From the results of slope map, 25-35° are highly vulnerable to landslide and also constitute larger percentage of landslide. This may be due to the fact that lower slope angle highly disfavor slide and in high slope angle, loose materials do not hold together, thereby decreasing the possibility of landslide. So, slope with moderate angle may be highly susceptible to mass movement phenomena. Also the land features which are near to river channels predominantly suffered from landslides. River has high scouring and cutting activity through the channel it treads, thereby undercutting the slope and making the upslope quite fragile, thereby increasing the chance of mass movement.

Most of the hillslope of the study area are composed of moderately to highly weathered rock such as quartzite, phyllite, slate, schist etc. Phyllites, slates and schists are highly weathered rock in which, the chances of landslide occurrence is high. From the hazard map of the study area prepared, high hazard area lies mostly on the edge of watershed area. This may be attributed to the presence of steep slopes and high hills surrounding the watershed. Most of the concentration of high hazard is predominantly in the west of watershed. Granite rocks are those which are generally considered as solid rock but it made up of tiny granules and when a small section of granule is displaced, slope failures can be observed. These rocks form a major part of the western part of Kulekhani watershed. Laban (1979) concluded that geological structure and lithology accounted for more than 75% of all observed landslides. Rainfall also accounts for the landsliding phenomena as in Nepal more than 80% of total precipitation occurs in monsoon period (Jun-Sept). Since very dry spring is accompanied by heavy rainfall in late summer, it is favourable climatic condition for the initiation of landslides in the study area. The disaster of July 1993 received tremendous amount of rainfall which may be the prominent cause for the landslide occurrence. Karmacharya (1989) studied the relationship between total annual precipitation and frequency of landslides during the period of 1971 to 1980 and found strong correlation between them. Petley *et al.*, (2008) found that rainfall pattern and monsoonal strength have direct relationship with higher number of landslides and vice-versa.

Final hazard maps were developed from frequency ratio method, statistical index method, landslide susceptibility analysis, weight of evidence modeling & certainty factor method. All the method resembles each other that all predicts high hazard zone ranges between 36%-39% and occurrence of landslides in high hazard area also shows a similar trend viz. 61%-66%. This high hazard area predicted from various statistical methods may attribute to the fact that the watershed area comprises of steep slope, rugged terrain, haphazard construction of roads, and high difference in elevation, extreme rainfall event due to changing climate, unscientific agricultural practice and deforestation. Pradhan *et al.*, (2006) produced landslide hazard map of the Kulekhani watershed by Landslide Index Method of Bivariate Statistical Analysis and found that 37.58% of the area falls under high hazard and other in moderate and low hazard areas. Also from their findings, they concluded that 70.09% of landslide falls within high hazard area. In this study also majority of landslides fall under high hazard area (61%-66%) which resembles the work earlier done in this regard and somehow shows the reliability of the hazard map. The figure below shows the landslide distribution with various hazard classes.

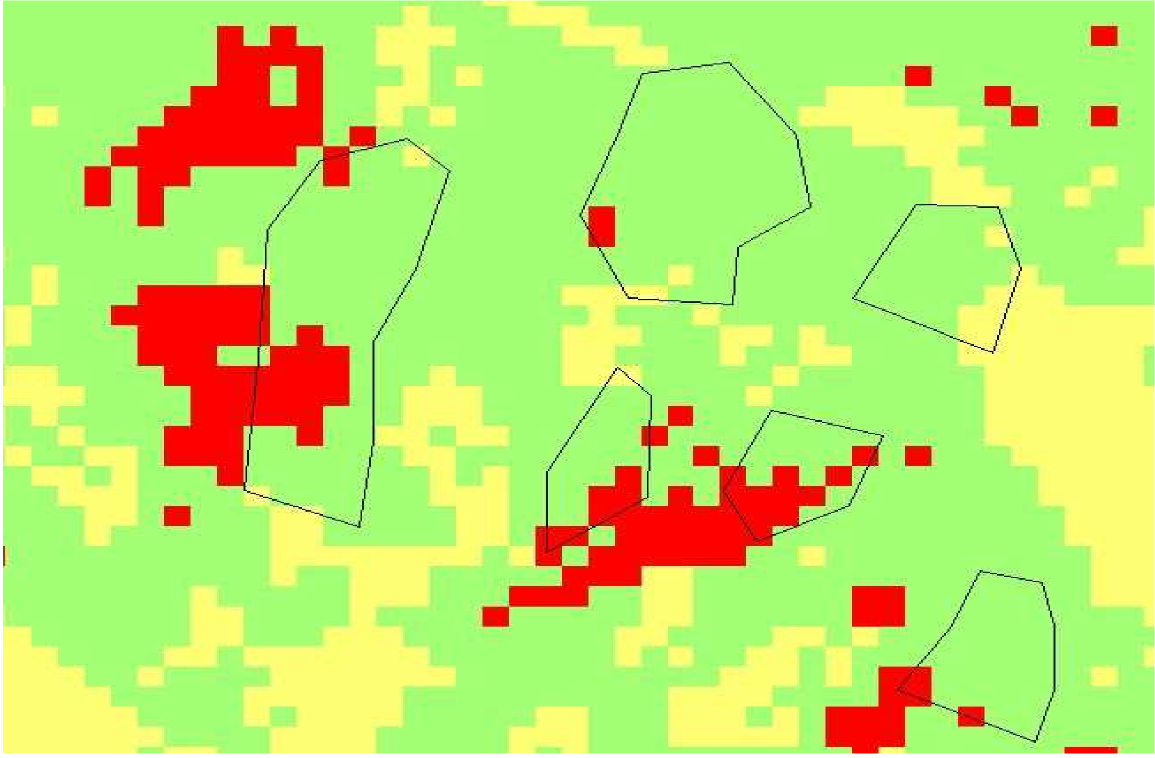


Fig 6.1: Examples of landslides overlaying LSZ map

From the figure above, we can notice that the landslides (polygons) are overlaying with different hazard class (red-high, green-moderate and yellow-low). Because in the inventory no distinction was made between the initiation part of landslide and the area of debris flows, there cannot be complete correspondence between LSZ classes and the complete observed landslide affected area. We consider a landslide a "good" prediction when at least part of it is situated in a high susceptibility zone. Thus, from the above snipped Figure 6.1, most of the landslides have some of its part in high hazard class which came good with our prediction.

An assessment of mapping prediction results indicated that at least 90% of landslides in the study area fall under high and moderate hazard class which means high number of landslides are reliably predicted. This result is relatively high with model prediction. So, it can be applied to practical research areas in order to prevent and alleviate damages due to crashes landslide can cause.

# Chapter 6: Conclusion and Recommendation

## 6.1 Conclusion

Landslides occur frequently in Kulekhani watershed in Makwanpur district. So, it is of utmost importance that the susceptibility map of the research area should be generated. The major factors contributing to the landslide in the study area which were included as factor maps are: 1) Slope 2) Aspect 3) Relief 4) Internal Relief 5) River Distance, 6) Landuse and 7) Geology

This research generated a series of landslide susceptibility maps using different "Bivariate Statistical Analysis" viz. Frequency Ratio Method, Statistical Index Method, Landslide Susceptibility Analysis, Weight of Evidence Modeling and Certainty Factor. The comparison made and results of all statistical approaches indicate that the all obtained LSZ map more or less agree on the extent of low, moderate and high landslide susceptibility class i.e. approximately 27% - 30%, 32% - 37% and 36% - 39% respectively. So a significant area lies in the high hazard susceptibility class. An assessment of results was carried out by including landslide in different susceptible class and found that in low, moderate and high landslide susceptibility class, percentage of landslide more or less is 8% -10%, 26% - 30%, and 62% - 66% respectively.

The conclusion resulted from the application of different statistical analysis methods for landslide susceptibility can be summarized in the following fronts:

- Larger percentage of landslide is occurring in areas with slope angle $25^{\circ}$ - $35^{\circ}$.
- N, NE and E facing slope are highly vulnerable to landslide.
- The elevation of 2000m-2300m favours the phenomena of landslide as larger % of landslide is occurring in this class.
- Internal relief in the class of 20m–30m and 30m-40m highly favour the landsliding phenomena.
- The area closest to river system has a huge impact in occurrence of landslide.
- Villages and built-up area disfavor landslide. The most favourable for landsliding is forest and cultivation area.

- Kulikhani Formation has a significant impact in vulnerability of the watershed.

Keeping in view, the research carried out by employing different “Bivariate Statistical Methods”, this researcher felt that the methods gave similar results in predicting the hazard map and also similar results in locating the landslides in high hazard area. So, any Bivariate Statistical Analysis Methods from the above mentioned five methods can be applied for landslide hazard zonation in the study area for future researchers.

## 6.2 Recommendations

Environmental hazard such as landslide cannot be entirely prevented and also lack of preparedness causes heavy losses both to human lives and economic activities. So, based on the hazard map preparation, some recommendation for remedying and preventing serious damages from landslides are given below:

- For the accuracy of the hazard map produced, more of the attributes that might be responsible for the causes of landslide should be included in future researches.
- Government should focus on sustainable development through safer infrastructural development and spreading knowledge of hazard and how to mitigate if the problem exist or persists.
- Any existing or future settlement plans should strongly consider using the landslide map in their planning processes.

# Landslide inventory form for Kulekhani Watershed

1. **General Information:**
    a. District:
    b. Nearest village:
    c. Landslide name:
    d. Date of research:
    e. Topo-sheet No.:
    f. Position: LAT: LONG:
    g. Identified by: field check/aerial photo/satellite
2. **Description of event:**
    a. Original state: Natural slope/Man made slope
    b. Slope curvature: Concave/Convex/Planar
       Convergent/Divergent/parallel
    c. Land use:
    d. Infrastructure:
    e. First indication:
    f. Activity: Dormant/Potential/Recent/Reactivated
3. **Type of landslide:**
    a. Kinematics: Fall/Topple/Slide/Flow/Spread/Complex
    b. Erosion: Gully/Sheet/Stream erosion
    c. Erosion stage: Initial/Mature/Old
4. **Geological and Engineering Geological situation**
    a. Soil type:
    b. Soil thickness:
    c. Attitude of bedding and joints:
    d. Attitude of dislocation plane:
    e. Average slope of slided mass:
    f. Ground water condition: dry/wet/damp/dripping/flowing
    g. Surface water condition: seepage/spring
5. **Causes:**

    **Geological causes:**
    a. High degree of weathering:
    b. High joint density:
    c. Wide joint opening:
    d. Strike of discontinuities parallel to strike of slope:
    e. Dip angle of discontinuities lower the slope angle:
    f. Massive bed over weak material
    g. Alternation of permeable beds:

    **Morphological causes:**
    a. Steeping of slope gradient:
    b. Erosion at slope toe:

    **Physical causes:**
    a. Increase in pore water pressure due to intense rainfall
    b. Earthquake

    **Man- made causes:**
    a. Steeping of gradient of slope:
    b. Excavation at toe of the slope:
    c. Overloading upper slope by construction:
    d. Deforestation:
    e. Leakage from irrigation canal/tap water drain
    f. Improper landuse practice

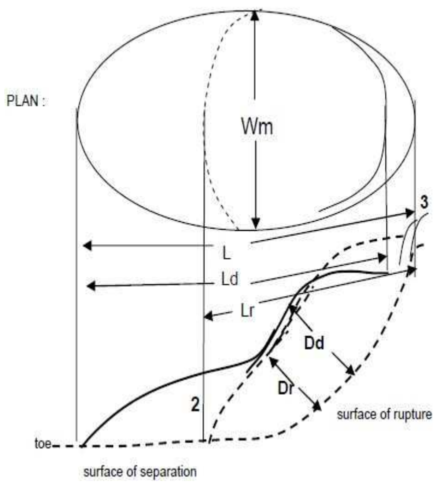
    **Triggering cause**…………………………………………………………………………
6. **Damage/Risk:**

    People/infrastructure/Metal road/Gravel road/Trails/Others

7. **Securing and stabilization measures:**
    a. Technical Earth works
       Removal
    b. Construction measures:

       Retaining-wall/Check-dam/anchor/nailing/protective rock wall net/dewatering/Bio-engineering
8. **Remarks**:…………………………………………………………………………
    …………………………………………………………………………………
    ……………………………………………..

## 9. Dimension of landslide (*If applicable in field*)



1- main body ☐
2- zone of accumulation ☐
3- main scarp ☐

L- total length (m) ☐

Ld- length of displaced mass (m) ☐

Lr- length of rupture surface (m) ☐

Dd- depth of displaced mass (m) ☐

Dr- depth of rupture surface (m) ☐

Wm- max width of the displaced material (m) ☐

## 10. Profile

| | | | | | | | | | |
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## 11. Sketch:

## 12. Photograph Numbers:

# Annex

**Table 1**

Landslide Probability of Different Landslide Mapping Methods

| | Area(sq. km) | Area (%) | Area of slide (sq.km) | Area of slide (%) | Landslide Probability |
|---|---|---|---|---|---|
| **Frequency Ratio Method** | | | | | |
| Low Landslide Susceptibility | 37.60 | 30.62 | 0.24 | 9.57 | 0.01 |
| Moderate Landslide Susceptibility | 41.08 | 33.45 | 0.71 | 28.01 | 0.02 |
| High Landslide Susceptibility | 44.12 | 35.93 | 1.58 | 62.41 | 0.04 |
| | | | | | |
| **Statistical Index Method** | | | | | |
| Low Landslide Susceptibility | 37.60 | 30.62 | 0.24 | 9.52 | 0.01 |
| Moderate Landslide Susceptibility | 42.06 | 34.26 | 0.73 | 28.77 | 0.02 |
| High Landslide Susceptibility | 43.13 | 35.12 | 1.56 | 61.72 | 0.04 |
| | | | | | |
| **Landslide Susceptibility Analysis** | | | | | |
| Low Landslide Susceptibility | 33.81 | 27.54 | 0.19 | 7.58 | 0.01 |
| Moderate Landslide Susceptibility | 41.89 | 34.12 | 0.68 | 26.82 | 0.02 |
| High Landslide Susceptibility | 47.08 | 38.35 | 1.66 | 65.61 | 0.04 |
| | | | | | |
| **Weight of Evidence Modelling** | | | | | |
| Low Landslide Susceptibility | 36.97 | 30.11 | 0.23 | 9.23 | 0.01 |
| Moderate Landslide Susceptibility | 38.24 | 31.14 | 0.66 | 26.13 | 0.02 |
| High Landslide Susceptibility | 47.58 | 38.75 | 1.63 | 64.63 | 0.03 |
| | | | | | |
| **Certainty Factor** | | | | | |
| Low Landslide Susceptibility | 33.09 | 26.95 | 0.19 | 7.32 | 0.01 |
| Moderate Landslide Susceptibility | 45.25 | 36.85 | 0.76 | 30.08 | 0.02 |
| High Landslide Susceptibility | 44.45 | 36.20 | 1.58 | 62.60 | 0.04 |

**Table 2**

Area of different classes of each parameter with their lanslide distribution

| Parameter | Class | Area in % | % of Slide |
|---|---|---:|---:|
| **Slope** | <15$^{o}$ | 26.93 | 11.37 |
| | 15-25$^{0}$ | 24.44 | 24.01 |
| | 25-35$^{0}$ | 26.63 | 33.80 |
| | 35-45$^{0}$ | 13.54 | 19.20 |
| | >45$^{0}$ | 8.46 | 11.62 |
| | | | |
| **Aspect** | N | 14.58 | 17.20 |
| | NE | 10.99 | 15.58 |
| | E | 17.62 | 23.87 |
| | SE | 10.23 | 9.62 |
| | S | 15.47 | 12.86 |
| | SW | 8.74 | 5.13 |
| | W | 13.70 | 7.57 |
| | NW | 8.68 | 8.18 |
| | | | |
| **Relief** | <1700m | 12.90 | 13.90 |
| | 1700-2000m | 49.86 | 30.89 |
| | 2000-2300m | 30.29 | 48.52 |
| | >2300m | 6.95 | 6.69 |
| | | | |
| **Int Relief** | <10m | 15.99 | 3.25 |
| | 10-20m | 25.18 | 18.27 |
| | 20-30m | 28.78 | 33.29 |
| | 30-40m | 19.96 | 31.37 |
| | 40-50m | 7.16 | 10.51 |
| | >50m | 2.92 | 3.30 |
| | | | |
| **River dist** | <25m | 23.70 | 36.30 |
| | 25-50m | 20.12 | 20.02 |
| | 50-100m | 29.11 | 19.34 |
| | >100m | 27.06 | 24.34 |
| | | | |
| **Geology** | Chandragiri Limestone | 5.02 | 1.04 |
| | Chisapani Quartzite | 0.58 | 0.74 |
| | Chitlang Formation | 8.47 | 2.49 |
| | Kulikhani Formation | 10.51 | 27.31 |
| | Markhu Formation | 11.31 | 13.32 |
| | Palung Granite | 29.39 | 37.77 |
| | Quarternary Deposit | 10.39 | 1.47 |

| | | | |
|---|---|---|---|
| | Sopyang Formation | 1.52 | 0.89 |
| | Tistung Formation | 22.80 | 14.96 |
| | | | |
| **Landuse** | Barren Land | 0.19 | 1.40 |
| | Buildings | 0.01 | 0.00 |
| | Bush | 7.44 | 9.38 |
| | Cultivation | 48.12 | 36.28 |
| | Forest | 42.42 | 52.62 |
| | Grass | 0.09 | 0.13 |
| | Nursery | 0.19 | 0.00 |
| | Sand | 0.49 | 0.17 |
| | Water Body | 1.05 | 0.02 |

**Table 3**

Rainfall Data of year 1993 in an around Kulekhani watershed area

| **Rainfall (mm)** | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **Months** | | | | | | | | | | | |
| | | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sept | Oct | Nov | Dec |
| SN | **Stations** | | | | | | | | | | | | |
| 1 | Chisapani Gadhi | 3.6 | 0.1 | 43.1 | 181 | 197.2 | 314.3 | 793 | 705.2 | 436.3 | 6 | 18.6 | 0 |
| 2 | Daman | 18.1 | 26.7 | 25.6 | 119 | 125.9 | 315 | 693.1 | 404.2 | 176.3 | 19.6 | 8.5 | 0 |
| 3 | Hetauda N.F.I | 14.3 | 10.5 | 46.8 | 79.9 | 141.1 | 275.1 | 831.7 | 738.1 | 259.5 | 26.5 | 0 | 0 |
| 4 | Markhu Gaun | 12.9 | 27.8 | 59.1 | 111.8 | 210.5 | 243.3 | 675.1 | 458.3 | 137.9 | 0 | 0 | 0.1 |
| 5 | Makwanpur Gadhi | 20.5 | 14.2 | 42 | 108 | 90.2 | 323.7 | 911.6 | 1003.5 | 369.8 | 98 | 0 | 0 |
| 6 | Beluwa | 12.5 | 56.7 | 35.3 | 89 | 140.8 | 247.1 | 604.8 | 649.5 | 258.8 | 50.7 | 0 | 0 |
| 7 | Rajaiya | 5.9 | 23.4 | 48.8 | 64 | 216.4 | 272.6 | 656 | 524.8 | 304.5 | 99.4 | 3 | 0 |
| 8 | Thankot | 29.3 | 49.5 | 59.8 | 124.1 | 166 | 194.6 | 593.2 | 597 | 184.4 | 0 | 0 | 0 |

Source: DHM-2011

## Some Photographs of the Study Area

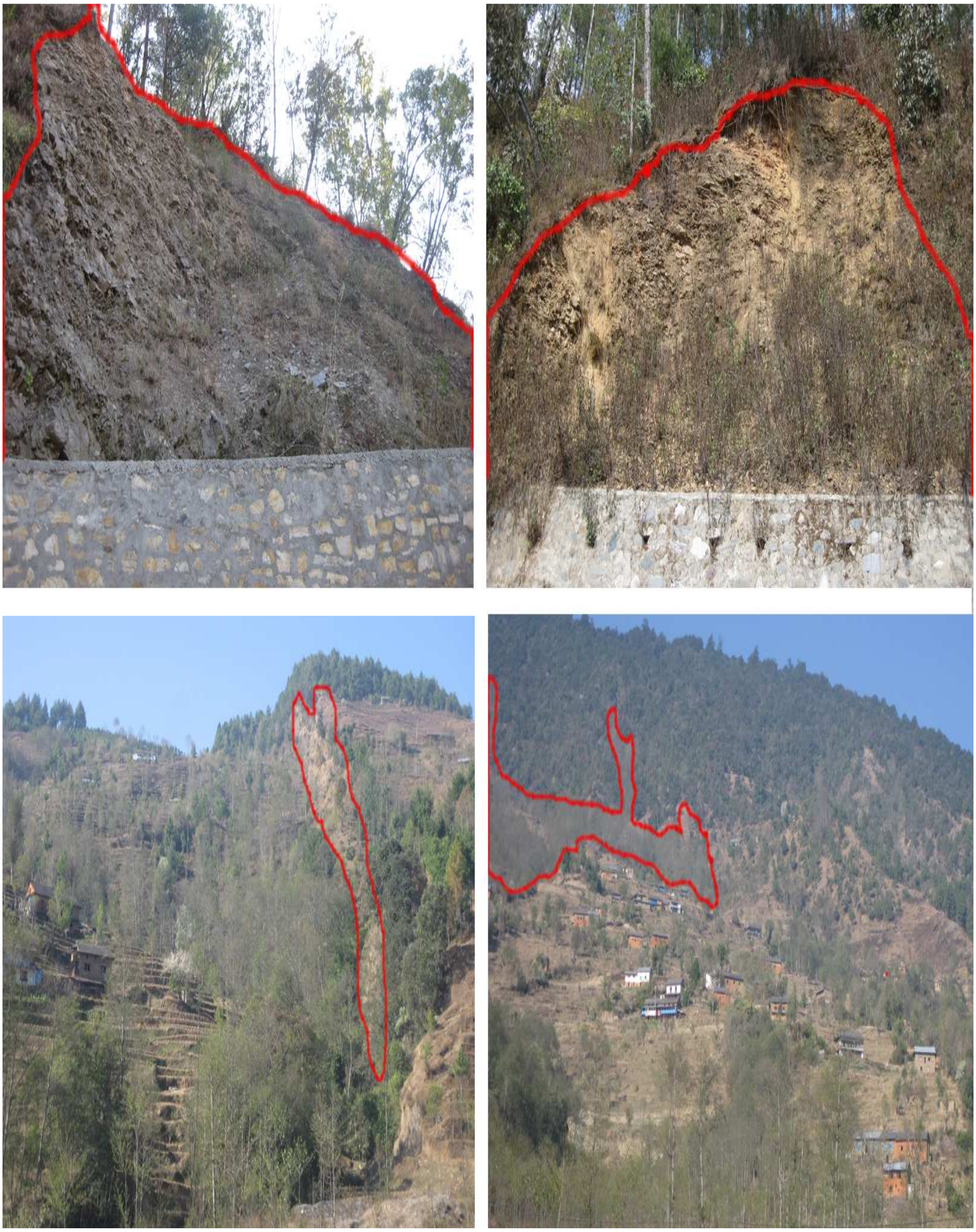

Photo 1: The red marked feature is either present or previous landslide

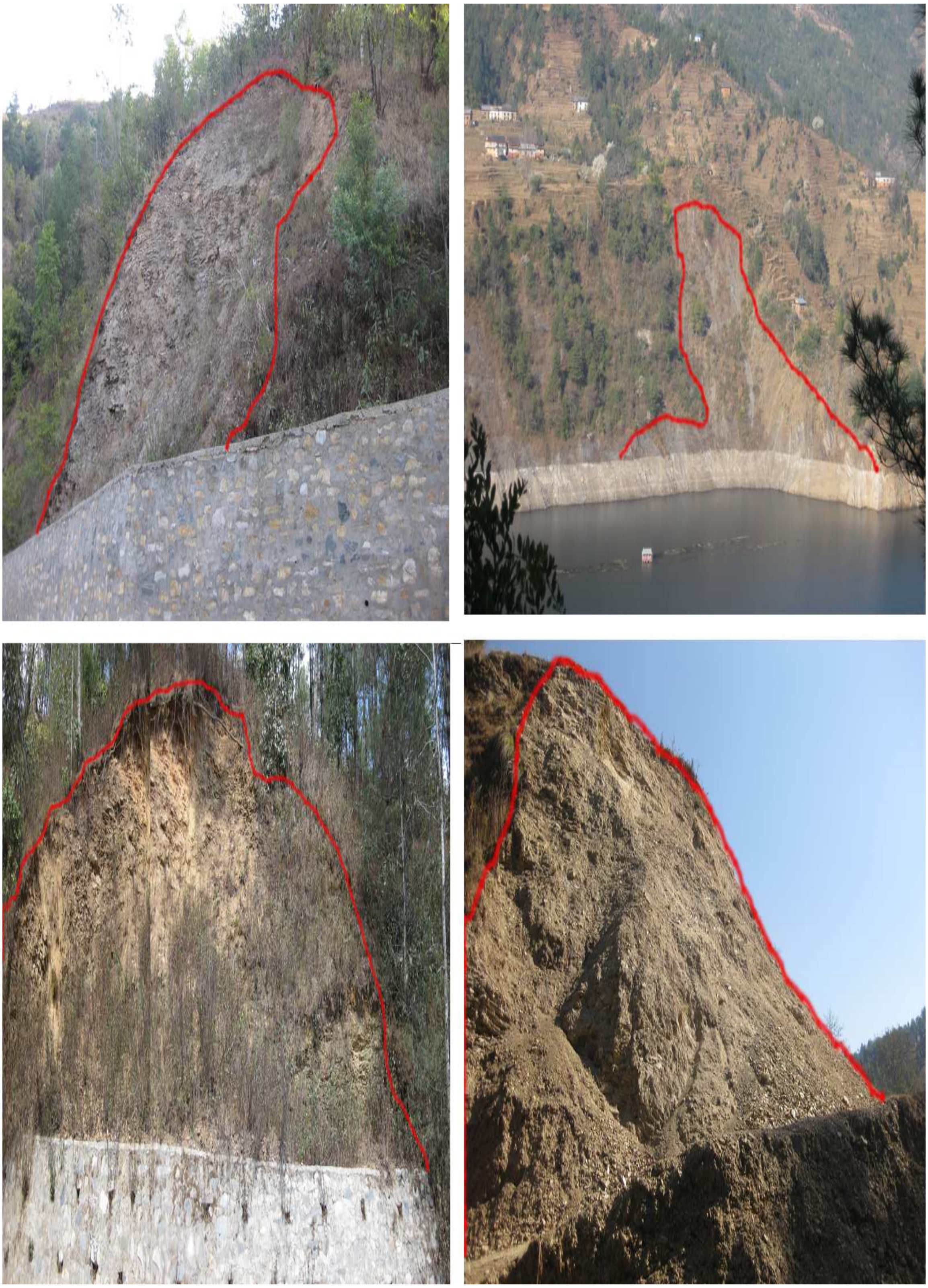

Photo 2: The red marked feature is either present or previous landslide

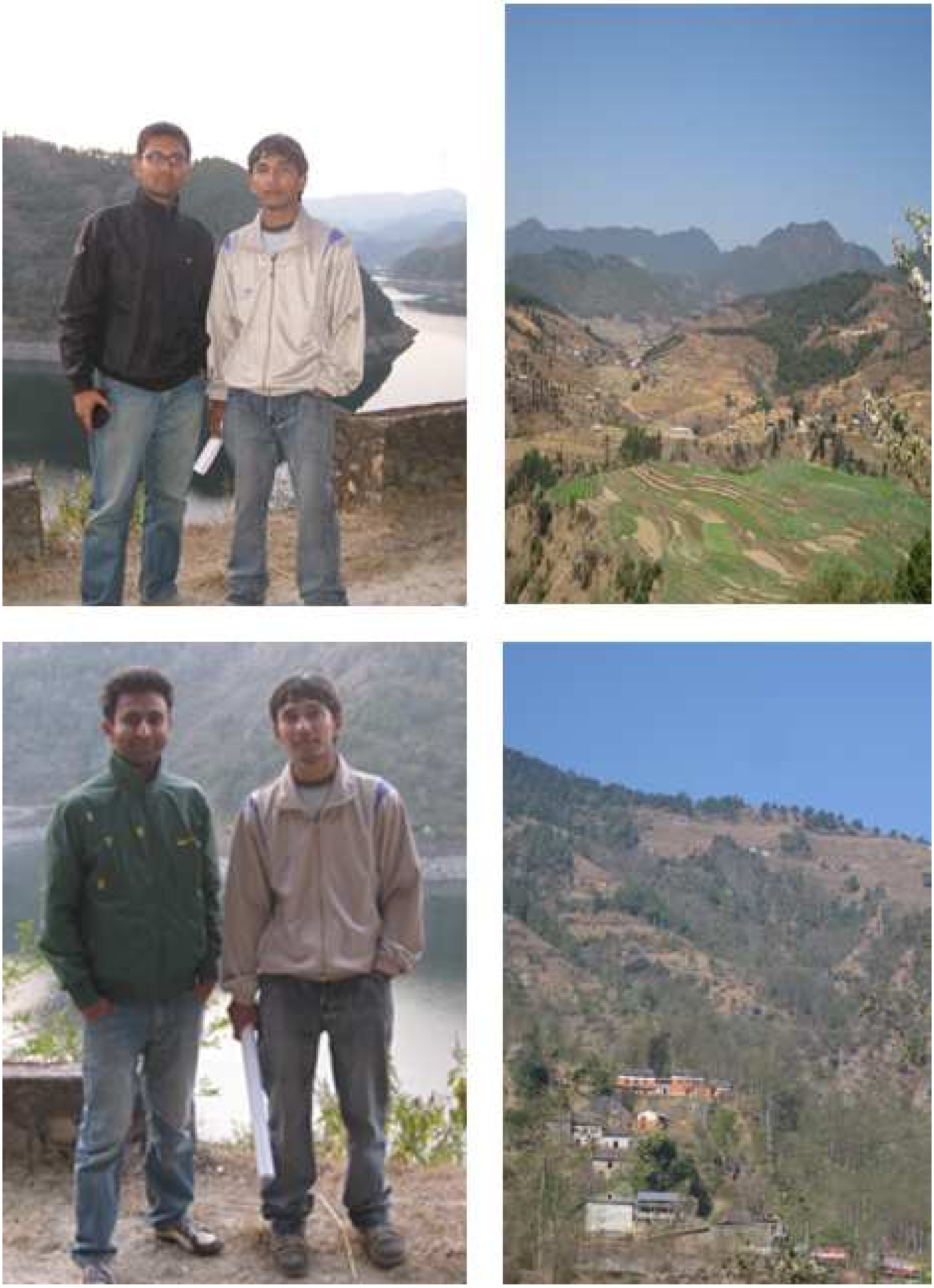

Photo 3: Areas depicting landuse and terrain

Photo 4: Areas depicting landuse and terrain

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