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Abstract

Geohazards refer to the hazards caused by various geological processes and conditions that lead to the damage of existing environment. Geohazards like landslides, earthquakes, tsunamis and snow avalanches are major issues of concern as they pose extreme risks worldwide. Approximately 1.4 billion of the world's population is vulnerable to these hazards. Thus, there is a need of addressing the risks associated with geohazards for creating a safer future.

The primary objective of this thesis is to broaden the knowledge of geohazard risks by understanding their potential causes, the likelihood of occurrence and their possible consequences. A concept for risk of geohazards is built on the basis of vulnerability, elements at risk and exposure. The risk of geohazards is highly influenced by complexity in human civilization and global climatic changes. Various uncertainties are also associated with geohazards, which needs a thoughtful strategy while making decisions. The qualitative method of risk analysis is adopted, on the basis of which a risk matrix is created.

In this thesis, some significant geohazards in Norway are discussed along with the factors leading to the future risk. As specifics of geohazards, the landslide issue of Nepal is taken. With the identification of triggering factors of landslides and their potential consequences, possible risk mitigation measures are suggested. A probability-consequence diagram is established that gives a clear picture of landslide hazard. Since risk categorization and severity ranking for consequences are subjective issues, an online survey was carried out. The ranking would be a great foundation for prioritizing prevention and mitigation measures in the nearest future and for decision-making matters.

Soil bioengineering techniques are prevalent for several years for the prevention and reduction of landslide hazards in Nepal. Herein, different factors affecting their suitability and efficiency are also discussed. It is concluded that there is a need of broader thinking to adopt new measures of risk management and design for the prevention and mitigation of geohazard risks.

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Abbreviations

ADPC	Asian Disaster Preparedness Center
AGU	American Geophysical Unit
ALARP	As Low As Reasonably Practicable
BBC	British Broadcasting System
CCKP	Climate Change Knowledge Portal
CRED	Centre for Research on the Epidemiology of Disasters
CRU	Climatic Research Unit
DAG	Directed Acyclic Graph
DHM	Department of Hydrology and Meteorology
DIMS	Disaster Information Management System
EM-DAT	Emergency Events Database
EWS	Early Warning Systems
GeoExtreme	Geohazards, climate change and extreme weather events
GIS	Geographical Information System
GSU	Geological Survey of Norway
HAZUS	Hazards United States
ICG	International Center for Geohazards
NGI	Norwegian Geotechnical Institute
NHRA	Nepal Hazard Risk Assessment
NORSOK	NORsk SOkkels Konkuranseposisjon
NVE	Norwegian Water Resource and Energy Directorate
RAC	Risk Acceptance Criteria
UN	United Nations
USGS	United States Geological Survey
c.a.	sine anno (Missing publishing year)

1 Introduction

1.1 Background

Geohazards refer to the threats caused by various geological processes and conditions that lead to the damage of the existing environment (Solheim et al., 2005; Nadim, 2009). These involve geological phenomena like landslides, earthquakes, tsunamis, avalanche, etc. They can exist on both onshore and offshore, and depend on the triggering factors for their occurrence. Mostly, the triggering factors for geohazards are natural; but in some of the cases, human activities and intervention can act as a triggering factor. For instance, mining is one of the human activities that can initiate geohazards.

Geohazards possess huge risk in the society. In general, the fatalities, as well as damages caused to the environment and the infrastructures, are used as a measure to estimate geohazard risks. Around the world, there occur many such events of geohazards every year causing massive catastrophes. These hazards affect many sectors of infrastructures annually. It is observed that the developing countries are more commonly prone to the risks and consequences of the geohazards compared to the developed ones. One of the biggest challenges after the occurrence of geohazards is to ensure the improvement of the living conditions of people and the environment. Thus, a better understanding of the geohazards is helpful in dealing with the risks associated with them and also in the possible prevention of (some) geohazards and the mitigation of the potential consequences.

Geohazards are the natural phenomena. Attention towards the assessment of risks imposed by geohazards to the human lives and the environment is given more light now than in the past decades. In the present days, many studies and investigations have been done on this subject for the mitigation of possible consequences, and these studies have helped people in many ways, to accept risk management as an alternative to the emergency management of geohazards (Nadim, 2009).

With a proper assessment of risks, the possible consequences can be minimized to some extent and risks can be lowered down up to a tolerable level. However, it requires a good coordination of both the national and international efforts that can help in developing a very efficient collective response to the risks of geohazards (Lacasse et al., 2012). Geohazards are unavoidable but with an appropriate risk assessment, an establishment of a cost-effective and socially acceptable management of built environment can be done. Threats can be minimized by proper evaluation of the geological processes and conditions of an area.

1.2 Objective

The main objectives of this thesis are as follows:

- To discover and broaden the knowledge and thinking over the geohazard risk concepts

- To identify various risks associated with geohazards, to analyze them and to suggest various preventive and mitigation measures
- To investigate the main geohazards in Norway and to discuss the future risk of those geohazards
- To determine the potential causes and consequences of landslides in Nepal, as they are taken as one of the geohazard issues in problem discussion
- To suggest possible mitigation measures for landslide hazards in Nepal
- To comprehend people's perception of landslide dangers by carrying out a small survey
- To establish a risk ranking and a severity ranking of the consequences of lanslides in Nepal
- To ascertain and discuss the factors affecting suitability and efficiency of soil bioengineering techniques in Nepal

1.3 Problem Statement

Every geohazard poses risks and impacts to both the human beings and the environment. Here in this thesis, we will be discussing the risks associated with them. We will discuss on landslide problems in Nepal, their causes, and consequences and also on the need of scientific research for soil bioengineering techniques in Nepal.

1.4 Outline of the Thesis

The first chapter of the thesis comprises of the introduction giving a thorough background of the topic. The second chapter consists of discussions on various geohazards and the major geohazards in the context of Norway. The Third part follows the concept of risk in our context with definitions of several related terms. The fourth part is the qualitative risk analysis of geohazards with discussions on risk assessment and risk management. As a major problem, "Landslide in Nepal" is considered, which is discussed in the fifth chapter following the sixth chapter of a risk analysis. Prevention measures for geohazards are discussed in the seventh chapter with a focus on the need for broader thinking. And the eighth chapter includes the concluding part with possible suggestions.

1.5 Limitations

- Geohazards can be both onshore and offshore, but this thesis covers the discussions on risks over the onshore geohazards only.
- Due to the limitation of time and resources, we lack a site/ field survey. And the risk analysis carried out is more subjective.

2 Understanding Geohazards

Geohazards are the events initiated by geological processes and conditions causing damage to the environment. The impact of geohazards is very significant for several years. On the worldwide basis, the database EM-DAT has recorded 6,873 natural disasters between the years 1994 to 2013, which claimed 1.35 million lives or almost 68,000 lives on average each year. In addition to this, 218 million people were affected on average per annum during that 20-year period. Table 2.1 gives a summary of impacts by various natural disasters (geohazards and climatic hazards) as presented in CRED report 2015.

Table 2.1: Summary of impacts on human by natural disasters between years 1994 to 2013 (CRED, 2015)

Geo-hazardous events	Number of people affected (In million)	Number of deaths (In thousands)
Flood	2400	160
Drought	1100	22
Storm	660	250
Earthquake (incl. tsunamis)	121	750
Extreme Temperature	93	160
Others (Volcano, Landslides, Avalanche, etc.)	13	20

Death rates during this period have increased tremendously due to major geohazards such as Indian Ocean Tsunami in 2004, Haitian earthquake in 2010, and Cyclone Nargis in 2008 (CRED, 2015). From the Table 2.1, we see that earthquakes (including tsunamis) alone have killed more people than all other hazards put together, claiming nearly 750 thousand lives.

A comparison of the disaster data for the year 2015 and a period of 2005-2014 is shown in Table 2.2.

Table 2.2: Summary of natural disasters (CRED, 2015)

	Year 2015	2005-2014 Yearly average
Number of country level disasters	346	367
Number of countries affected	113	116
Number of deaths	22,773	76,424
Number of people affected	98,580,793	173,241,621
Economic damages (US$)	66.5 billion	155.8 billion

Country level disaster data and the number of countries affected for the year 2015 is almost equal to that for 2005-2014. This shows that the year 2015 has solely been a year of great disaster. In this year, 346 natural disasters were recorded that claimed 22,773 lives and affected around 98 million people. It caused an economic damage of 66.5 million US dollars. Furthermore, the largest geohazard of 2015 regarding fatality was the earthquake in Nepal that resulted into a death of more than 9,000 people and a loss of more than 5 billion US dollars. Globally, Asia is counted as the most affected continents by such disasters regarding occurrence (44%), persons killed (72%) and persons affected (60%).

2.1 Some Common Geohazards

2.1.1 Landslides

The movement of a mass of rock, debris and soils due to the deep failure of the slopes due to gravity is called landslide (ADPC, 2010). The soil features, slope stability, and other such geological conditions must be looked upon for the reasons behind a landslide. Apart from this, the climatic conditions, the amount of rainfall and the environmental ecology also play a vital role in this geological phenomenon.

Global warming has also increased the risks of landslides. A huge change in the climatic conditions due to global warming has triggered unusually more rainfall, changes in the hydrological and meteorological conditions and more precipitation due to the melting of snow in the high mountains and Himalayas. Landslides are the natural phenomena, but the probability of their occurrence and their severity are affected mostly by our actions. For example, carrying out deforestation for building the livelihoods or some other purposes increases the possibility of landslides directly. Perhaps, there are other triggering factors like rainfall, storms, earthquakes, etc. which must be considered. High frequency and magnitude of landslides can result in other hazards like earthquakes and volcanoes.

Unlike other geohazards, the impacts of landslides in the society and the economy of any country have been given less importance (Nadim, 2009). Hence, people are less aware of the risks of landslides. But as presented in the statistics from CRED, landslides contribute to at least 17% of all the fatalities from natural hazards worldwide. Though the loss of human lives due to landslides is not so massive in comparison to that of other hazards, their effects are relatively long term. The potentiality of landslides to destroy any structure depends largely on the materials involved like rocks, soil, water, etc. and subsequently on their mass. An immense change in the hydrology, destruction of the habitats and loss of the productivity of the cultivable lands are observed due to landslides, which have great impacts on human lives (de Blasio, 2011, p. 3).

Many incidents of landslides are observed around the world every year. Figure 2.1 shows the landslide in Lidong Village in Zhejiang province of China, which had incurred on 13 November 2015. According to (BBC, 2015), heavy rainfall had stimulated a large amount of mud, rock, and debris, causing the landslide. It engulfed many houses killing 25 people, and several got missing. Along with this, the continuous heavy rainfall during and after the landslide resulted in more flooding into the village and also hampering the rescue works.

Figure 2.1: The Lidong village landslide in China (Lyme, 2015)

Figure 2.2 shows the flood caused by heavy rainfall and blockage of water channels by the landslide in Lidong Village.

Figure 2.2: More rainfall resulting flood in the Lidong village after landslide (Lyme, 2015)

The changing climatic condition was predicted to be the primary cause of heavy rainfall, thus leading to such a massive landslide in the village. It affected more than 87,000 people, as mentioned by (Lyme, 2015). It destroyed many cultivable lands and damaged various infrastructures like roads. The damaged road can be seen in Figure 2.1.

The impact of landslides is immense and long-term. Landslide hazard and risk assessment have become a topic of major interest for both the geoscientists and engineering professionals in the recent years. The increase in public awareness regarding the socio-economic impacts of landslides and the environmental impact of the development and urbanization have been the two key reasons for increasing interest in landslide hazard assessment.

2.1.2 Earthquakes

Risks posed by the earthquakes are regarded as one of the greatest of all the geohazards in the world. They have tremendous effects in densely populated areas with the unorganized settlement. They increase not only the number of fatalities around the world but also increase damages to a society and the country. Every year, different countries face different magnitudes of earthquakes. The devastation caused by them depends on their magnitude. According to USGS, The Haiti Earthquake (2010) of magnitude 7.0 causing the death of more than 300 thousands of people, Tangshan Earthquake of China (1976) causing the deaths of more than 240 thousand, are the major earthquakes recorded to date. The total fatalities and damages caused by them are even higher. Earthquake is such a geohazard that can initiate other hazards like landslides, snow avalanche, floods, and tsunamis.

Larger earthquakes cause shock waves because of which the tremors are felt for some seconds. But these aftershocks last longer with the increase in distance from the epicenter. The severity of an earthquake is highly dependent on the amplitude and the frequency of the wave motion. It also depends on the geology of the ground on which buildings and structures are standing and their construction mechanisms. Estimating the risks and consequences of a seismic hazard is a difficult task. There has not been any particular method developed for forecasting the exact size, location or time of an earthquake. However, (Bell, 2003, p. 76) mentions that with an observation of the past patterns of the seismic activities, a reasonable prediction is usually made.

There was a massive earthquake in Japan recently. However, April 2015 Nepal Earthquake is taken as an example here. As reported by UN, it killed over 9000 people and injured more than 23,000 people. Thousands of the houses were destroyed across many districts affecting a total of 8 million inhabitants around the country. Apart from this, it also initiated landslides in various hilly regions of Nepal. Snow avalanche was triggered on Mount Everest, which caused deaths of several foreigners and local people. A valley named Langtang, situated on the lap of Himalayas, was completely wiped up by the avalanche triggered by this massive earthquake. It damaged many infrastructures like roads, hydropower plants and collapsed several buildings, cultural heritages, monuments, etc. Figure 2.3 shows a complete destruction of several parts of Kathmandu Durbar Square, one of the UNESCO World's Heritage Sites.

Figure 2.3: Aerial view of destroyed cultural heritages due to earthquake in Nepal (Park, 2015)

We have discussed earlier that different geohazards can initiate several other hazards. As reported by (Park, 2015), Nepal earthquake 2015 had set off snow avalanches leaving a large number of climbers dead, missing, injured or trapped on Mount Everest. Figure 2.4 shows a photo depicting the avalanche site on Mount Everest.

Figure 2.4: Snow avalanche in Mount Everest (Park, 2015)

Earthquake hazard assessment can be carried out in various ways. HAZUS is an approach for earthquake risk calculation and is based on the capacity spectrum method, combining the ground motion input regarding a response spectrum with the building's specific capacity curve, i.e., spectral acceleration versus spectral displacement (Nadim, 2009). It is a software system prepared for use in the United States by Federal Emergency Management Agency and it uses GIS (Solheim et al., 2005). The capacity of the buildings differs according to their type, building code regulations and on the basis of their location and construction. The capacity curve varies accordingly by these factors. HAZUS implies on data collection using database maps of soil type, ground motion, ground failure, classifying building occupancies and their form, describing the damage state, grouping and ranking the lifelines and then developing an output that gives the likely risks estimated from an earthquake.

2.1.3 Tsunamis

Tsunamis are the seismic waves of very long wavelengths. They are generated by the sudden displacement of the seafloor due to various mechanisms other than earthquakes. These waves are created by any of the activities like volcano, earthquake or landslides that displace water from the sea with a massive amount of energy sufficient to wipe away a settlement and infrastructures (Veitch & Jaffray, 2010, p. 226). Similar to earthquakes, tsunamis are also known to be devastating worldwide because of the millions of fatalities and billions of economic damages they have caused.

The Indian Ocean Earthquake of December 2004 of magnitude 9.1-9.3 had triggered a series of deadly tsunamis. As from the records of USGS, it killed over 230 thousand people, 12 thousand missing and more than 1 million people displaced. Of the fatalities recorded, 168 thousand were from Indonesia alone (Veitch & Jaffray, 2010). Figure 2.5 is a map showing the Indian Ocean Earthquake and Tsunami.

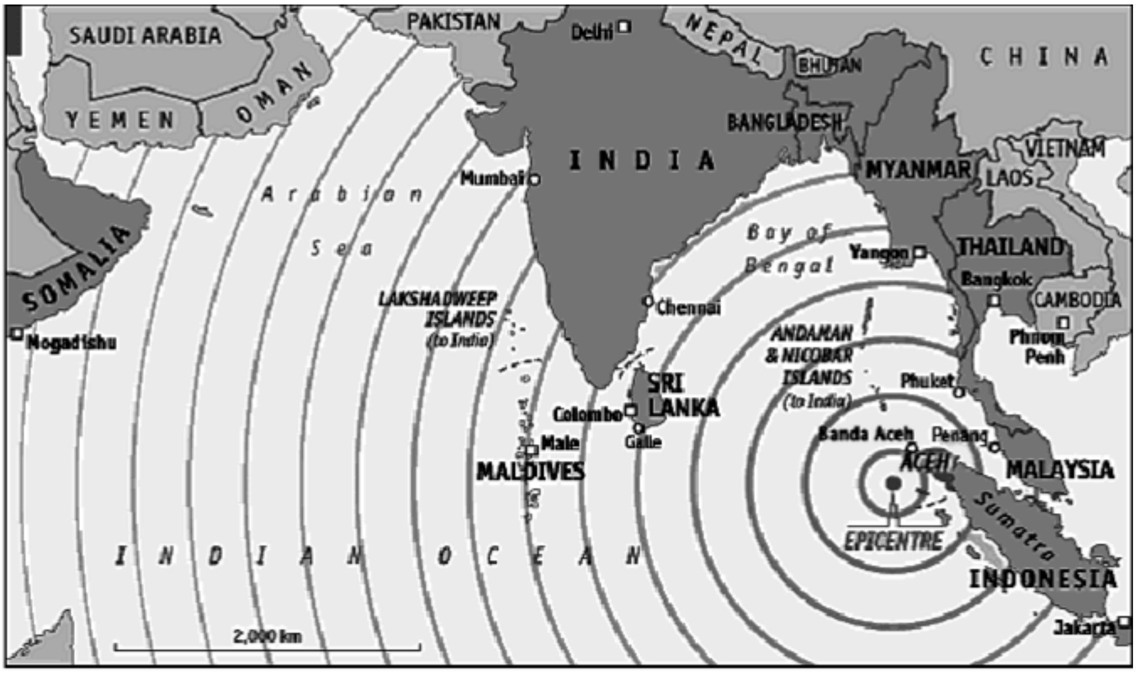

Figure 2.5: Map of the 2004 Indian Ocean Earthquake and Tsunami (Veitch & Jaffray, 2010)

Apart from this, it affected some other countries, affecting million of people. Tsunamis have great impacts on human lives and coastal environments, causing not only the loss of lives but also the destruction of the coastal ecosystems and habitations, and destruction of many infrastructures. The initial assessment after the occurence of any hazards are focused mainly on the basic needs. However, the recovering phase is long and challenging because of costly and time-consuming reconstruction and rehabilitation activities.

(Lacasse et al., 2012) mention that earthquakes have generated 75% of all the tsunamis around the world. Submarine landslides and rockslides into the bodies of water also initiate tsunamis. Hazard and risk assessment of tsunamis was not a major topic of focus until the enormous devastation of 2004. However, in the present day, many organizations and researchers have been working on the risk and mitigation measures. Tsunami risk evaluation is the combination of tsunami hazard, exposure, and vulnerability. The vulnerability to tsunamis depends on various factors such as tsunami flow depth, wave current speed, wave current acceleration and inertia and the momentum flux. Measurement of these parameters helps to determine the damages caused by tsunamis.

2.2 Geo-hazardous Issues in the context of Norway

Norway comprises of more than 100 thousands kilometers of long coastline and 10 thousands of lakes along with extensive fjord system in most of its western parts (Hermanns et al., 2014). Because of having many deep-sided valleys and the adverse climate, landslides are very common. In addition to this, several climate variables are known to be potential triggers of geohazards in Norway (Dyrrdal et al., 2011; Jaedicke et al., 2008). Also, the extreme weather conditions are preceded by a complex interaction of meteorological and geological processes acting at short and long time scales. Triggering factors are further complicated by local and regional variations in the snow cover and geology. Identification of these triggering variables is rather difficult as many hazardous events are a consequence of the joint contribution of many factors. Likewise, according to (Hermanns et al., 2014), more than 270 various events of rock falls, rock avalanches, debris flows, quick clay slides, snow avalanches, and submarine landslides have been recorded so far from the fourteenth century. Exposure of Norway's population to the displacement waves generated by the impact of subaerial landslides and to the tsunamis produced by the movement of submarine landslides has increased the risks of geohazards. More than 2000 fatalities and considerable damages to the infrastructure have been caused by landslides and avalanches over the last 150 years (ICG, 2006; Jaedicke et al., 2008). The fatality posed by any of the hazards in Norway is quite smaller in comparison to that of other countries because of low population density. However, the economic loss and damages to the environment are significant. Of the geohazards, occurrence of an earthquake is a rare phenomenon in Norway. Snow avalanches, Rockfalls and rock avalanches and quick clay landslides are the most common geohazards in Norway (ICG, 2006; Jaedicke et al., 2008). As per (Jaedicke et al., 2009), most of the fatalities in Norway is accounted due to snow avalanches, while most of the damages to the infrastructures and properties have been due to larger rock slides causing flood waves and massive quick clay slides. Three major geohazards in Norway are discussed in the following sections.

2.2.1 Quick Clay Landslide

Quick clay formation takes place in the pockets of marine clay when there is a substantial amount of groundwater flow through it. It possesses a firm character unless it is disturbed. However, when it is overloaded, it then starts to flow like a liquid. As a result, the loose grain structure of the clay collapses and quick clay landslides begins to develop. It is usually triggered by various natural factors like river erosion, heavy rainfall or by the human activities like digging and mining. The occurrence of quick clay landslide depends on the terrain, the location of the clay within the ground and its relation to other deposits or bedrock (GSU, 2015).

Norway comprises of about 5,000 square kilometers of its area covered by marine clay deposits (with 20% highly sensitive quick clay). Quick clay landslide is a serious geohazard in Norway that comes up with many environmental challenges. The societal and environmental risks increase significantly with this hazard. Quick clay slides in exposed marine sediments represent an unusually high risk in eastern and central Norway but do also occur in parts of western and northern Norway (Jaedicke et al., 2008). There have been two major quick clay slides in Norway in the past nineteenth and twentieth century. The Verdal slide in 1893 is the largest quick clay slide in Norway, which had caused a fatality of 116, with an involvement of about 55 million cubic meters of clay. Similarly, the Rissa slide in 1978 was also the biggest one covering an area of 330,000 square meters and 5-6 million cubic meters of clay pouring out of the slide area (Kalsnes et al., 2014). These kinds of major quick clay slides do not occur frequently, but the yearly occurrence of small quick clay slides is common, which increases the risks associated with them.

A larger number of population dwell in quick clay areas in Norway. The triggering factors for quick clay slides are mostly influenced by human actions. Risks related to quick clay slides are carried out by classifying the potential slide areas on the basis of “engineering scores” (Lacasse et al., 2012), which is based on evaluating the geology, local conditions, and exposed publics and assets. This method has been developed by NGI along with the works carried out by the NVE. In this approach, risk and hazard classes are described as low, medium and high, and the consequences as not severe, severe and highly severe. Land topography, geology, geotechnical conditions and the changes caused by human activities and natural processes like rainfall, soil erosion, etc. play a significant role to signify the level of hazard.

There has recently been an incident of quick clay landslide on February 2015 at Vestfold, Norway as seen in Figure 2.6. As per (AGU, 2015) this slide caused one of the main pillars of the bridge to slip from the foundation and eventually deformation of the road deck. Since quick clay slides can be triggered by slight disturbances, investigators have anticipated that the activities of the bulldozer had triggered the occurrence of the quick clay slide because they observed the dozer doing some re-profiling works seen at the slide area.

Figure 2.6: Quick clay landslide collapsing the bridge at Vestfold, Norway (www.vg.no)

2.2.2 Rocks or Rock Avalanches

Norway comprises of many fjords along with a long coastline due to which rockslide avalanches or the rock falls are more prevalent. They are also considered as a serious geohazard in Norway because of their potential to cause tsunamis. Rockslides into the fjords have caused the largest number of fatalities in Norway in the twentieth century by generating a tsunami. Tafjord 1934, and Leon 1905 and 1936 were three major rockslides that created large flood waves (Böhme et al., 2015; Solheim et al., 2005). More than 174 people lost their lives in the northern-west Norway in the past decade due to this hazard. And in the worldwide context, the disasters caused by such events are even more. Recently, a catastrophe drama movie called The Wave (Bølgen in Norwegian) was made. As Norway is a rockslide prone country, this movie is based on those major rockslide tsunamis (Wave, 2016). It presents a picture of threat due to such geohazard and the situations one has to tackle for safety, at the last moment of the disaster. It reflects a battle against time in order to save the lives.

The vulnerability and risks associated with rock slope failures are increased due to several reasons. They are unfavorable climatic conditions like heavy precipitation, extreme snowmelt in springs, and the long frost periods in the glacially over-steepened slopes (Böhme et al., 2015). The Western part of Norway and the Troms area in the northern Norway are mostly prone to large rockslides generating huge tsunamis in the fjords (Jaedicke et al., 2008). In the present day, Åknes rockslide in western Norway is considered as the most dangerous rockslide in Norway. Hence special attention has been paid.

Rockslides usually occur in the weaker areas where the slope has a relatively low gradient (<45^0). Usually, heavy rainfall or extreme loads like earthquakes can trigger rockslides. In the context of Norway, rock avalanche source areas have been grouped by (Braathen et al., 2004) as:

1. Rockfall areas
2. Rockslide areas
3. Complex fields

This classification is based on pre-avalanche deformation patterns and is shown in Figure 2.7. They can further be sub-divided on the basis of structural geometry and the style (way) of deformation.

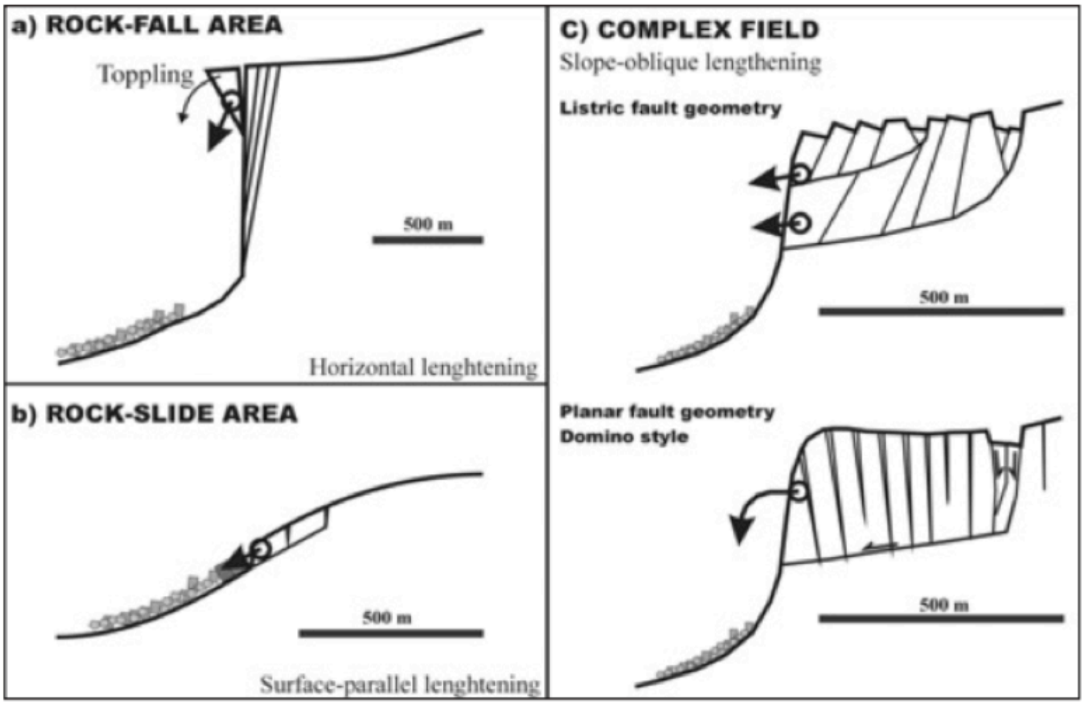

Figure 2.7: Geometrics of rock-slope failure (Braathen et al., 2004)

Mitigation measures for the rockslides include hazard mapping, monitoring, early warnings and registration of potentially unstable rock slopes.

2.2.3 Snow Avalanche

Snow avalanche is a phenomenon of fast moving of snow masses along with the rocks, soil, and vegetation from any slopes. The increase in a load of snow usually causes a snow avalanche. This loading is dependent on various factors like land terrain, the amount of precipitation, the wind, temperature, etc. There are two ways by which the formation of the snow avalanche can be approached. The first one is the exploration of the terrain, snowpack and the meteorological conditions by any association or statistics. This method is implemented by most of the avalanche forecasting organizations. And the second one is the study and modeling of the physical and mechanical processes of an avalanche formation. It is relatively a physical approach (Schweizer et al., 2003).

Risk associated with the snow avalanche is more dependent on the speed at which the snow is deformed and the temperature of the surrounding. Slopes more than 30 degrees tend to have a slab avalanche. Snow cover varies in space, which is called as spatial variability. Wind is the most significant causes of spatial variability. It is a crucial factor for slope stability evaluation and avalanche formation and also one of the major sources of uncertainty in avalanche forecasting. Besides these factors, properties of ice also play a vital role in this phenomenon. Environmental as well as other conditions that influence the occurrence of snow avalanches may change over time. Hence, it is very important to consider all these factors too while evaluating the risks of snow avalanches in present day situation.

As per NGI, there used to be fatalities due to indoor accidents by snow avalanche in Norway. But in these days, fatalities are observed due to outdoor activities like skiing or driving across a mountainous road. Risks of snow avalanche are growing. Therefore, continuous concerns regarding prediction and mitigation are necessary. Snow avalanche is also one of the serious geohazards in Norway. According to (ICG, c.a.), there were more than 2000 fatalities in avalanches of various kinds over the past 150 years. 1500 of those fatalities were from snow avalanche alone. Altogether 161 people lost their lives in the year 1868, because of which it is regarded as the worst avalanche year.

Figure 2.8: Damaged houses by snow avalanche in Longyearbyen, Norway (Newsdesk, 2015)

Figure 2.8 shows a picture of damaged houses by a snow avalanche in Longyearbyen. Longyearbyen is the main settlement of the remore Arctic island called Svalbard. According to (Newsdesk, 2015), several people got missing and ten houses were destroyed by the avalanche. The avalanche was assumed to be connected with snow storm too.

Snow avalanche has always been a major geohazard every year. In Norway, the counties of Hordaland, Sogn and Fjordane, Møre and Romsdal, Nordland, Troms and the coastal mountainous regions of West-Finnmark usually have snow avalanches during winter. Snow avalanches affect large parts of western and northern Norway and these are the geohazards, which most frequently lead to loss of lives and infrastructure damages (Jaedicke et al., 2008).

In Norway, NGI has its own snow avalanche research station, Fonnbu, in Grasdalen valley in the Strynefjell Mountains. It is one of the most avalanche prone areas in Norway. Empirical data on snow and weather conditions are collected and they are compiled here. Then all the avalanche areas are mapped and warnings on snow avalanches are issued. However, Norway lacks a countrywide avalanche warning system. In addition to this, assessment of snow avalanche hazard is rather complex and difficult task because there hasn't been development of any automatic avalanche warning systems. A special website (www.snoskred.no) owned by NGI is in use at recent, which consists of current information on avalanches and snow and weather conditions.

Snow avalanche is a rare and irreproducible event, which makes the quantitative understanding of this phenomenon quite difficult and narrow. Avalanche hazard has been described by (Bakkehoi, 1987) as a product of the probability for an avalanche to occur, the size of the avalanche and the consequences. Furthermore, a detailed analysis of snow avalanche hazard by using this method can be found in (Bakkehoi, 1987). We cannot stop the occurrence of snow avalanches but as a risk analyst, our target is to reduce the hazards of snow avalanche to an acceptable level. So far, acceptance level of snow avalanche risk has not been established yet. In recent years, research and studies are seen on this issue. Hazard mapping and zoning are usually adapted for this purpose. Hazard mapping implicates determining the probable extent of snow avalanche. Tools like air photographs, analysis of past records, studies of snow and climatic data and so on are generally used. Land-use planning plays an important role in avalanche risk management and mapping the possible hazards. But there is a lack of knowledge in determining the role of snow avalanches in the coupled geomorphic process chain.

2.2.4 Future Risk of Geohazards in Norway

Various incidents of snow avalanche during every winter and a recent landslide hazard near Voss indicate that Norway is at risk of geohazards. According to (Berglund, 2016), the slide was massive with more boulders, trees and rocks sliding onto the E16 Highway and out of the fjord. It caused inconvenience in carrying out emergency operations too. With these kinds of landslides and rock falls or snow avalanches, there is a risk of losing lives, while on the other hand; they block the roads causing impacts on the traffic. Consequently, the risk increases due to such effect in traffic as the exposure groups and vulnerability increases. Temperature and precipitation have a great influence on geohazards in Norway (discussed in Section 2.2). Norway's land profiles being lengthened over latitude, these elements vary consequently, increasing mostly during winter seasons. (Jaedicke et al., 2008) points out to an increase in the likelihood of situations leading to geohazardous events due to the regional climatic changes. It foretells about rising frequency and strength of extreme weather events in Norway in the next 50 years. In this issue, a 4 year (2005-2008) project called GeoExtreme was run in Norway, which focused on investigating the coupling between meteorological factors and landslides and avalanches, extrapolating this into the near future with a changing climate and estimating the socio-economic implications. (ICG, 2006; Jaedicke et al., 2008) explain in detail about this project.

Along with the increasing risks of rockslides and tsunami related floods, there is also a great spatial variability in snow depth in Norway due to the presence of coastal, mountain and inland climates (Dyrrdal et al., 2011). Central and mountainous regions of Norway comprise of largest depth of snow, while the coastal regions have less. Increasing trends of precipitation and wind speed in mountainous and central regions as seen in (Dyrrdal et al., 2011) refer to increasing frequency and risks of snow avalanches in the nearest future. As many as ten major snow avalanche disasters can be expected over the hundred years leading to a plentiful loss of life if necessary steps are not taken (NGI, s.a.). However, some uncertainties have to be faced during this analysis of trends of climatic conditions and snowfall. Uncertainties arise due to complex land topography of Norway. Despite the researches and projects been carried out on geohazards in Norway; there is a need to focus on formulating plans and strategies on regional basis. This will be helpful for creating the spatial variation of climatic conditions at various parts of the country. It also adds effectiveness in mitigative plans. There is also a need of more scientific research on changing geohazardous conditions by evaluating the past hazards, their occurring patterns and potential triggers. This helps to prevent socio-economic risks in the nearest future as well as to improve mitigation strategies. In addition, prediction of possible geohazards with the changing climatic conditions can also be useful in reducing the future risks. Increasing public awareness of geohazards and establishing a geohazard-focused program is necessary (Solheim et al., 2005). Furthermore, it adds that there is a need to improve the basic understanding and our ability to deal with the risks associated with them.

Mitigation of hazards is an essential task for minimizing the probable risks and consequences. These measures can vary for any specific situations and the prevailing geohazards. Success of such measures relies on reliability of the implemented measures. But in some of the cases, existing knowledge gap on proper understanding of hazardous situations and the relevant uncertainties associated with them can cause difficulty in quantifying the efficiency of mitigating measures. Hence, it is necessary to carry out an assessment regarding the effectiveness of mitigation measures for that particular scenario. In addition to this, one should ensure that the applied mitigation measures fulfill a particular level of safety, quality and sustainability. It is suggested to start projects focused on proper investigation and monitoring of unstable rock slopes, snow avalanche and other hazard prone areas. An observation on past failure activities should also be carried out for estimating future occurrence and risks of geohazards. Similarly, early warning systems for any predictable events should be enhanced in the case of Norway so that people can be alert beforehand.

Evacuation systems and escape routes should be prioritized for safety against the future hazards. Avoidance of settlement on hazard prone areas like quick clay zones and under unstable slopes, can to some extent be useful in reducing vulnerability, and subsequently, the future risk.

3 Concept of Risk for Geohazards

According to (Aven, 2008):

"Risk is described by (C, C*, U, P, K), where C equals the consequences of the activity (including the initiating events A), C* is a prediction of C, U is the uncertainty about what value C will take, and P is the probability of specific events and consequences, given the background information K."

It is a general definition of the term 'risk'. Description of risk differs context wise, but the primary information it holds is the same for everything. The consequences that a situation brings can be different depending upon the extent and the nature of the initiating event. According to (Aven, 2008), a risk picture is established on the basis of cause and consequence analysis and it addresses the following factors:

- Predictions of consequences
- Probability distribution
- Uncertainty factors
- Manageability factors

Understanding the scenario of risk and factors mentioned above and also being able to analyze the possible causes and consequences can be useful in creating a risk picture for any particular situation. Risk generates at any place where there exists a potential source of damage or loss to a target. In the case of geohazards, the source is a hazard (earthquake or landslide, etc.) and the target is the people, assets, and the environment. (Aven et al., 2013) have schematically represented a risk as in Figure 3.1.

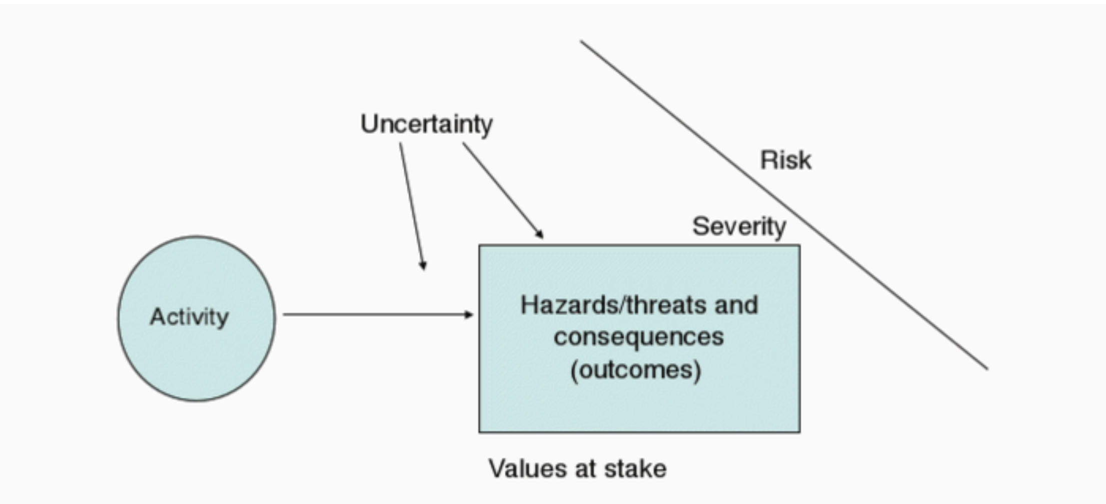

Figure 3.1: The concept of risk reflecting hazards/threats and consequences and associated uncertainties (what events will occur and what consequences will be) (Aven et al., 2013)

The basic concept of risk can be understood more clearly by the above diagram. It shows that the occurrence of an activity leads to a hazard that results in some consequences. There are also some uncertainties associated with the activity regarding the possible consequences, and the understanding of uncertainties is crucial. Consequences relate moreover to the adverse effects, but there can be positive outcomes too. The risk is more centered to the unwanted or undesirable results and consequences. However, there is no risk where the people and values are not exposed to any hazards. Thus, an appropriate definition of risk depends on the group who are likely to face the consequences and are vulnerable to any hazards.

The risk of geohazards is more comprehensible by understanding the terms associated with it. It helps in selecting a proper risk analysis as well as suitable mitigation measures. We discuss them in following headings.

3.1 Vulnerability to Hazards

Vulnerability, as defined in (Blaikie et al., 2003, p. 11), is the characteristics of a person or a group to anticipate, cope with, resist and recover from the impacts of any natural hazard. It comprises of various factors that determine the degree to which people's lives and properties are put at risk. It is the capacity of an individual and is usually influenced by hazardous situations. Vulnerability differs on various bases like people's status, gender, ability, living standard and the environment. Inhabitants in a prone area are equally vulnerable to a hazard, but these factors make the difference in vulnerability. For example, people living in hilly areas are more susceptible to landslides than those living in plain lands. Vulnerability varies on the type of housing and the value one can afford for the preparedness against a disaster. Similarly, the consequences of a geohazard for the richer group of individuals are far less severe than for the surviving poor. Moreover, it can thus be elaborated that usually it takes more for the poor and developing countries to cope with the hazards than for the richer and developed countries. (Blaikie et al., 2003, p. 92) have made a clear illustration of this difference in vulnerability in agreement with socio-economic factors.

Vulnerable are those group of people who are more likely to be affected by any hazard. According to (Cutter & Finch, 2008), vulnerability analysis helps in the identification of such sensitive group of people who have fewer tendencies to cope with and recover from a disaster. Also, the composition of vulnerability is driven by exposure, sensitivity and response, and it requires the measurements of both the environmental and social systems.

The vulnerability of a group often changes with time and space. (Cannon, 1994) divides vulnerability into three aspects. The first one is the degree of resilience of a particular individual or a group or a livelihood system and their capacity to resist the impacts of a hazard. It reflects economic resilience. The second aspect is the health component that includes both the robustness of individuals and the operation of various social measures. And the third point is the degree of preparedness of any person or group, which depends on how people act on his or her behalf for a given hazard. Preparedness is the ability to protect oneself from the dangers, and it relies mostly on the strength of the livelihood and the type of relationship that he or she holds with the society or the state.

When the discussion is about vulnerability, it is necessary to understand the term 'resilience'. In general, it is the capacity of any physical and human system to respond to and recover from extreme events or hazards. Social, economic and political factors determine the level of resilience. These factors also determine people's vulnerability. Reducing vulnerability can be helpful in reducing the effects of a geohazard. (Cannon, 1994) further mentions about the alteration of vulnerability profile and argue on the fact of being risky to rely on the development of scientific knowledge and technical means of hazard reduction. Advanced technologies for risk mitigation may have little or no effect in some of the cases. As an example, expensive and advanced scientific warning systems are used. But there will be no single (beneficial) impact on the people who are out of reach of the signals or who can't pay for (or don't have) the means of communication like radios, through which they can get the warnings. The effectiveness of such warning systems lies on people's affordability to the means and being in the range of the measure. To some extent, this fact draws the attention that underdeveloped countries are more vulnerable to hazards concerning both the lack of preparedness actions and their level of likelihood and resilience.

Reducing the vulnerability to hazards is always a great challenge. Thus, it is important to look at the factors on which vulnerability to a given hazard depends upon (Nelson, 2014). They are:

- Proximity to a possible hazardous event
- Population density of the particular area regarding the event
- Scientific understanding of the hazard
- Public awareness
- Existence of the early warning systems
- Availability of emergency means and equipment
- Construction styles of buildings and infrastructures
- Social and cultural factors influencing people's response to any warning

Having a thorough understanding and knowledge of these factors helps to understand the vulnerability to any geohazard and get prepared for the harsh situations that may occur.

3.2 Severity

Severity, as defined by (Aven, 2008, p. 19), is the intensity, size or extension of a hazard concerning something that humans value (lives, the environment, money, etc.). Consequences are characterized on the basis of severity. It is an assessment of possible impacts of a hazard, usually defined by losses and gains on assets expressed regarding money or a total number of fatalities. The severity of consequences is usually greater in urban areas as there are more population and more developed infrastructures, which consequently denotes to increased exposure groups leading to the higher potential of losses. Similarly, our actions also influence the severity of consequences like the location of human habitats, the ways in which existing natural environments are modified, how constructions of buildings are made, etc.

A risk assessment matrix can be generated by combining the probability of hazard occurrence and severity level of possible consequences. This model is useful in the qualitative assessment of risk. According to (Blaikie et al., 2003), variations in the level of vulnerability to geohazards are fundamental in distinguishing the severity of the impact of a disaster on different groups of people. Recovery from a hazard is directly dependent on the level of its severity.

3.3 Elements at Risk

Elements at risk refer to the population, buildings, infrastructures and several other environmental and economic features of any particular area, which are likely to be affected by a hazard (Westen et al., 2006). The potential loss of any of the socio-economic factors increases with an increase in the elements exposed to any danger. It consequently increases the risks. The quantification of elements at risk is done either regarding numbers (number of buildings destroyed, the number of fatalities, etc.) or monetary value (costs of construction compared to the cost of repairment, reconstruction or replacement) or by their importance (historical, geographical, etc.). It may vary with time and space and also on the nature of the geohazard.

An assessment of elements at risk is necessary before carrying out vulnerability analysis. Moreover, vulnerable groups refer to elements at risk. One should also focus on these aspects while preparing and planning risk mitigation measures.

3.4 Risk of Geohazards

The concept of risk is much wider than what we understand in general. Furthermore, the limitations for expressing the uncertainties associated with any event must also be lightened for a better understanding of risk. The concept of vulnerability broadens the concept of risk associated with geohazards because vulnerability is something, which cannot be ignored. It refers to the degree of exposure and how susceptible the target groups are about any source of hazards. Vulnerability plays a significant role in determining the risk. A little exposure to something that is highly hazardous may result to low risk while to a high exposure leads to high risks. Also, the perception of risk differs on various bases like the experience one has gained from any adverse event, the social background, one’s ability to cope with that situation and so on.

(Kron, 2002) has given an example in his paper which makes a clear understanding of the term risk. Let us take an example of an earthquake. If it occurs in the region where there is no any habitation or structures, it is not regarded as dangerous. Similarly, the same earthquake will also be non-catastrophic in a well-organized region. However, for a poorly prepared area with many inhabitants, even a small tremor of an earthquake can be a devastating catastrophe. The earthquake hazard is clearly the highest in the first case, but the risk of an earthquake is the largest in the third case. Therefore, a conclusion can be drawn that three constituents determine risk in relation to the geohazards. They are:

a) Hazard (threatening natural event)
b) Exposure (the values/humans present in the region where a hazard has occurred)

c) Vulnerability (lack of resistance to the destruction caused by the hazard)

Collectively, risk about geohazards is a combination of hazard, exposure and vulnerability as shown in Figure 3.2. How much you are exposed to any threat can solely define your vulnerability to hazards. Since the hazards is the natural phenomena, it can neither be stopped nor be ignored, but by understanding these three terms and their relation, probable consequences can be evaluated and risks can be mitigated. Risk can be expressed in this case as:

Risk = Hazard × Vulnerability × Exposure

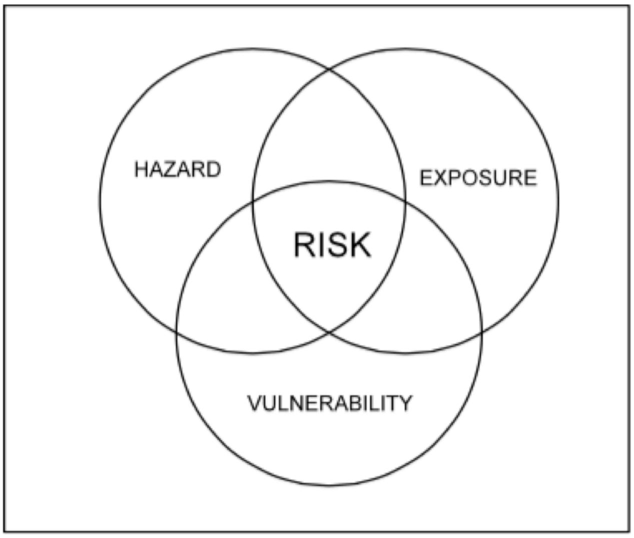

Figure 3.2: Risk as a combination of hazard, exposure and vulnerability

Similarly, the risk is defined as a measure of probability and severity of an adverse effect on life, health, property, or the environment. Mathematically, (Kalsnes et al., 2010; F. Nadim, 2009; Norsok Standard, 2001) has represented risk of geohazard as:

Risk = Hazard × Potential worth of loss

This potential worth of loss refer to the vulnerability of elements at risk. Hence, the risk of any geohazard is a combined function of a hazard and the number of population or assets in an environment, characterized by their varying degrees of vulnerability to that particular hazard, who occupy the space and time of exposure to that hazard event (Blaikie et al., 2003).

3.5 Sources of Geo-hazardous Risks

Risks arise from various probable sources which lead to several consequences. Either it is a component or a system; identification of potential sources of threats can be helpful in the analysis of their outcomes and subsequently, to the mitigation of risk. Geohazards are such events that pose risks to the human livelihood as well as to the society. On the other hand, uncertainties increase the risks associated with hazards. One is aware of the fact that hazards cause a significant imbalance in the environment and the livelihood, but the uncertainty in their occurrence, time and location make the people a bit skeptical. Nobody knows about what magnitude of an event turns out to be a great disaster and what implications it may bring to the society and the environment.

We cannot create the risks from geohazards as geohazards are the natural events occurring due to some geological conditions and processes. They bring risks along with them, and this is a natural phenomenon. However, human behavior and actions influence the nature and the extent of such risks (Murphy & Gardoni, 2011). It implies that people cannot create hazards but their activities directly or indirectly influence the probability of occurrence of some of the hazards. It also depends on how we construct and modify the built environment with the virtue of how we alter the natural environment. Let us take landslide as an example here. It is such kind of geohazard whose probability of occurrence and severity are more affected by our activities. We modify the existing environment for various purposes like settlement and road constructions by cutting down the trees. When there is rain, then there are high chances of the soil being washed away or sliding of the slopes. Our activities directly increase the likelihood and severity of landslides and the risks too. Risks in the context of geohazards commonly refer to the losses of lives, damage to the structure, and imbalance in the environment (ecosystem). Besides, they also depend on the knowledge and information distributed among the social groups regarding that particular geohazard. It is thus, important to figure out the sources of geohazard risks due to which various consequences arise for both the human and the environment.

In many of the cases, the sources of hazardous risks increase with an increase in complexity in human civilization. A typical example here is; the way structures (buildings) are constructed. It can alter the survival of people. Weak structures or the structures built without following appropriate building codes and standards are usually prone to damage from hazards. Besides, the increasing population density at a place increases urbanization. It directly affects the vulnerability to geohazards, consequently increasing the sources of risk. Similarly, it is not every time that people lose their lives during the dangerous period. There have been various examples of individuals who have survived the hazard at the moment of their occurrence, but later lose their lives coming under the consequences of geohazards like falling buildings and structures. There had been many such casualties during Nepal Earthquake 2015 too. Hence, a better understanding of the influence of human interactions on geohazards is necessary to minimize the possible sources of risks to society or a country.

3.6 Socio-economic and Changing Climatic Impacts on Risks of Geohazards

Socio-economic factors have a great impact on risks of geohazards. They refer to the number of population, their livelihood and their social and economic statuses in a community. The literacy rate is also one of the socio-economic factors which highly affects both proper understandings of geohazards and response to preparedness. In other words, how the economic aspects influence one's social status relate these factors. The world’s exposure groups to geohazards have inevitably increased with growing population and infrastructures. (Banholzer et al., 2014) mentions as per a study released in 2012 that around 60% of the population living in urban areas, with more than one million inhabitants (in 2011), are living in regions at risk from geohazards. It means, approximately 1.4 billion of the world’s population is vulnerable to hazards. The poorest communities are mostly susceptible to geohazard risks because their limited economic status makes them being unable to afford for a living in safer areas or cope up with the dangers of geohazards, or provide for emergency services during such situations. Hence, the limited economy compels many people to live in hazard-prone areas like unstable slopes, floodplains and coastal zone.

Changing climate is a major issue in present days. It is one of the consequences of actions of growing population and urbanization. It has affected many fields including the occurrence of future geohazards too. Climatic changes lead to changes in magnitude, frequency, duration as well as the timing of weather conditions, which results in an extraordinary extreme weather and climatic events. But geohazard like earthquakes is not influenced by climatic changes. Variations in the global climate like changes in heat waves, too much increase or decrease in temperatures; unusual rainfall, etc. are observed worldwide. As an example, melting of glaciers due to increasing temperature, increased precipitation or melting of snow in mountains increase slope instability which, lead to the occurrence of geohazards like landslides and snow avalanches. There is a need for a combination of knowledge of the experts regarding future climate changes with the knowledge of disaster risk management regarding vulnerability, adaptation and consequence analysis of geohazards. This combined experience helps to increase efforts for minimizing risks of hazards and hence contribute to creating a sustainable environment.

Socio-economic factors and global climate change are inter-related because human beings and their increasing complexity in living standards have profoundly influenced change in weather. This complexity refers to increasing urbanization, development of massive infrastructures, increase in pollution, etc. Steady growth in global population and urbanization has increased the exposure rate around the world, ultimately causing an increase in fatalities from induced geohazards like landslides and earthquakes (Nadim, 2009). Risks of geohazards and their potential consequences highly depend on socio-economic factors of existing environment. In addition to this, the magnitude and frequency of extreme climatic events also influence such risks. Risk therefore largely follows urban and regional development, which means economic risk increases with growing population and exposed assets (Banholzer et al., 2014). Hence, investigation of the factors that influence changes in global climate is necessary. An establishment of appropriate strategies can be beneficial for preventing the probable consequences and reducing the risk of geohazards.

4 Risk Analysis of Geohazards

Risk analysis is a process carried out to describe risk by which, one can be able to establish an informative risk picture, compare various alternatives and solutions, and identify critical factors about risk and express the impacts of different measures of risk (Aven, 2008, p. 5). Ultimately, risk analysis provides a basis for choosing the best alternative solutions with a documentation of acceptability and safety level of risk. Risk analysis of geohazards is about identifying the degree of risk, estimating that risk and then evaluating it for prevention of any potential consequences. From risk concept in Section 3.4, three basic things should be taken into consideration. The first one is the elements at risk, which defines the probable items that are affected by the hazards. The second one is the vulnerability of these elements. And the third one is the likely damages or effects that are caused due to the hazards. The degree of risk depends on one's vulnerability. Different elements have a different level of vulnerabilities, which must be analyzed.

A risk picture comprises of various building blocks for every scenario. A similar risk picture is established for geohazards (as shown in Figure 4.1) on the basis an example given by (Aven, 2008, p. 4).

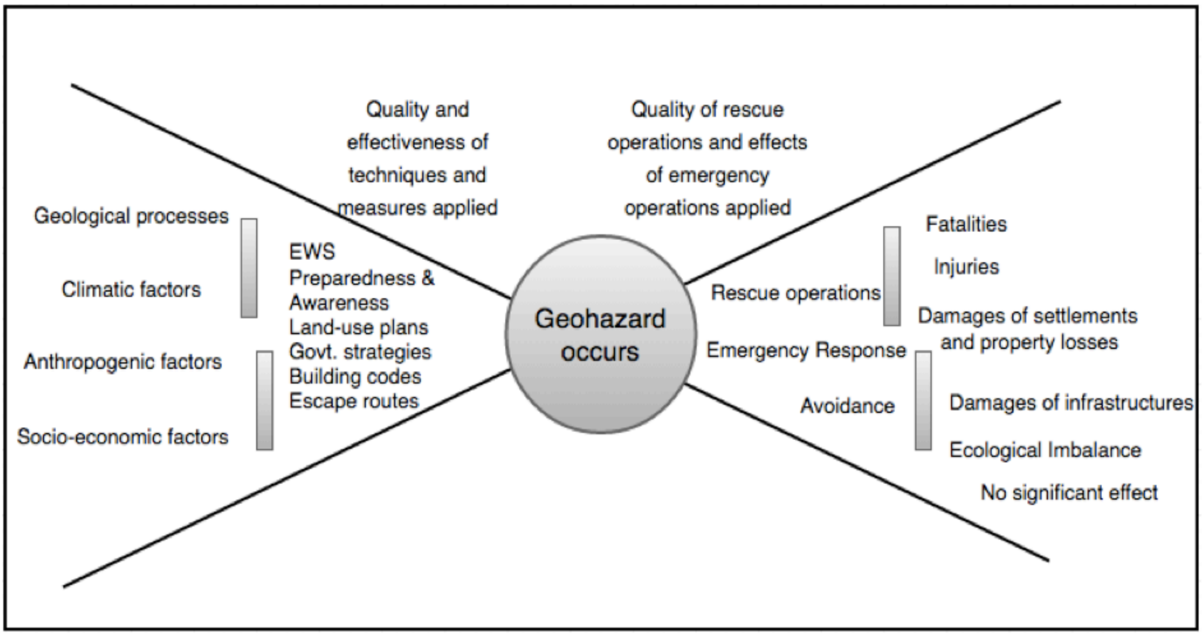

Figure 4.1: Bow tie for a geohazard risk picture

On the very left of the bow tie, casual factors of geohazards are present, which are geologic processes, climatic causes, socio-economic and anthropogenic causes. Various barriers exist that restrict the occurrence of geohazards. In our case, these barriers are the mitigation and prevention measures like EWS, public awareness, government strategies and so on as shown in Figure 4.1. Despite the restrictions, a geohazard occurs, which possesses various consequences. As soon as the geohazard occurs, several steps are carried out to minimize the effects. These measures are emergency operations, rescue operations and avoidance. Nevertheless, consequences like fatalities, injuries, damages of structures, etc., can be observed. In this process, uncertainties in quality and effectiveness of mitigation measures lead to the occurrence of the geohazard. Similarly, changes in quality and effectiveness of emergency operations result to several degrees of consequences. In this way, we can define a risk picture for a geohazard.

4.1 Risk assessment

Risk assessment is more about quantification of the vulnerability of the elements at risk. It can be achieved by making an evaluation of the degree of damage that may result from the occurrence of a geohazard. Quantification is usually done regarding monetary values or concerning the number of structures and population affected. Consequences of a hazard are measured and then compared with the costs of hazard mitigation. But, all risks imposed by geohazards cannot be measured and assessed in terms of cost. Particularly, risk assessment is all about determining the nature and the extent of risk associated with an activity and is composed of three basic steps. They are (a) Identifying the relevant sources of risk or threat or hazards; (b) Analyzing the cause and consequences and (c) Describing the risk. In overall, risk assessment helps to create a risk picture. Risk assessment is a part of an integrated risk management process (Kalsnes et al., 2010). It plays a vital role for urban planners in making the further decision regarding the planning and mitigation of risk, taking the vulnerability of people and urban structures in consideration about the probability of occurrence of an event. Risk analysis comes under risk assessment process and has the principle objective of improvement of the planning process and reduction of the vulnerability and mitigation of possible damages (Bell, 2003, p. 5).

Figure 4.2 shows a framework for a risk assessment process as given by (Norsok Standard, 2001). Risk assessment and mitigation for geohazards suggested by (Lacasse et al., 2012) is also based on this framework. It is a quantitative risk assessment framework. Besides geohazards, it is applicable for risk assessment of many other fields. A small discussion of the steps included in this framework is done under following headings.

i. Establishing Context

Establishing the context is all about identifying a scenario about any hazard. It covers the evaluation of all the activities that are carried out in the initial phase of risk assessment and all other measures that are implemented to ensure that the risk evaluation process is performed well and can meet its objectives. In this step, the scopes and activities of a risk assessment process are executed so as to maintain a qualitative level in the evaluation process. The primary purpose and responsibilities of the risk assessors must be defined clearly. Also, the methodologies to be implemented and tools to be used for the entire process should be defined. A proper establishment of context helps in achieving a reliable risk picture and in making a right decision for the prevention and mitigation of hazards.

ii. Hazard identification

Hazard Identification involves a comprehensive and thorough identification of a hazard, which may be a landslide or an earthquake or a snow avalanche or so on. It gives information like the magnitude of the danger, place of the hazard occurrence, etc. A geohazard is identified by a geological study of any particular location, its climatic conditions, hydrology and the influence of nature and man-made activities.

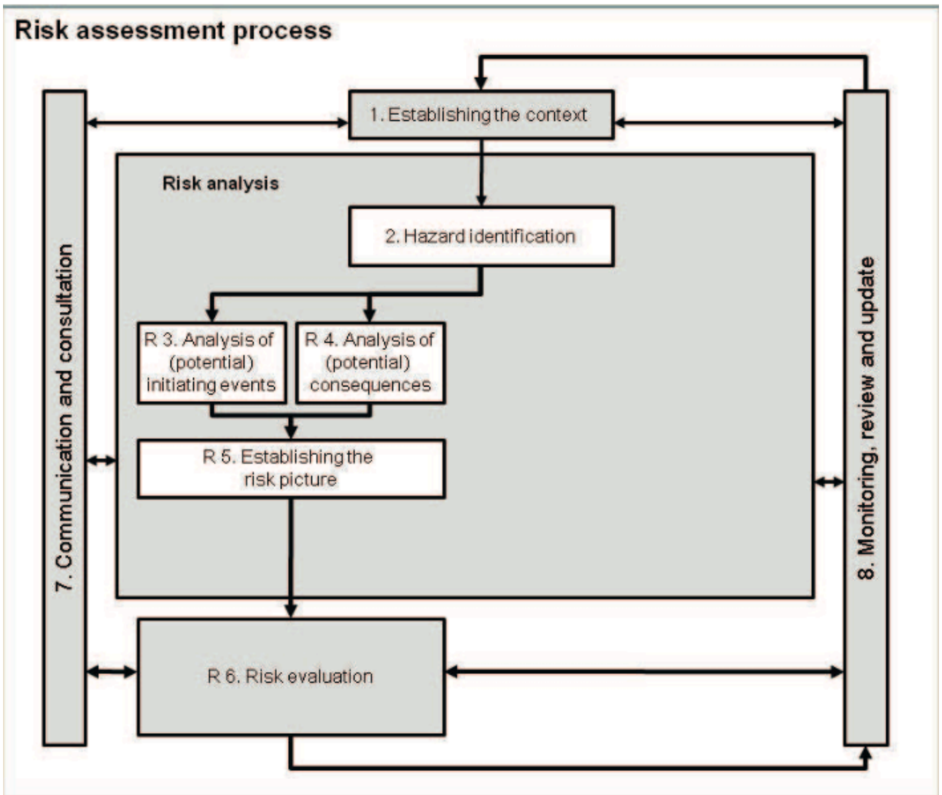

Figure 4.2: Risk assessment framework (Norsok Standard, 2001)

iii. Analysis of Initiating Events

The events that lead to the occurrence of a hazard are analyzed in this step. The geology of any place and its conditions and human actions upon an environment are common triggering factors for most of the geohazards. Analysis of initiating events can help for the minimization of probable consequences and also the risks associated with them. It is also helpful in identifying the elements at risk. Documentation of initiating events can be useful to make a comparison between initiating events of previous/past geohazards. Hence, it provides an underpinning of knowledge so that right decisions can be made for preparedness, response and recovery from geohazards.

iv. Analysis of Potential Consequences

A hazard always brings impacts to the society and environment. Consequences of geohazards are mainly observed in the form of a total number of lives lost and the damages that have happened to the existing infrastructures and properties. Losses are estimated for all the elements at risk. An analysis of consequences can be useful to make the comparison with the total costs of mitigation. It will be helpful for making plans and strategies.

v. Establishing the Risk Picture

A risk picture is established as a useful and understandable synthesis of the entire risk assessment process. It provides information to the decision makers regarding the acceptable criteria of risk and to choose the best measures for risk mitigation. Uncertainties associated with hazard analysis are also addressed along with the selection of the most appropriate risk treatment strategy.

vi. Risk Evaluation

Possible risk reducing measures are proposed with the analysis of the elements at risk and their potential consequences. The risk is estimated by assigning a probability of damage. It is then evaluated as acceptable or not and whether additional risk reducing measures are required or not. Consequently, the decisions are made concerning the level of risk.

4.2 Risk Management

(Lacasse et al., 2012; Nadim, 2009) define risk management as a group of organized activities usually performed with the objective to reduce risk by assessing, directing and controlling the risks posed by hazards in the society. Furthermore, various policies, procedures and practices are applied in a systematic manner to identify, analyze, evaluate, monitor and implement risk mitigation measures. Risk management deals with making a balance between the disagreements associated with opportunities on one hand and avoiding losses, accidents and disasters on the other (Aven, 2008). It integrates the recognition and assessment of risk with the development of appropriate treatment strategies. It focuses on creating a level of protection that alleviates vulnerabilities associated with geohazards and their potential consequences, so as to reduce risk to an acceptable level. For this reason, it is essential to understand fundamental components of geohazard events like the type of threat, their frequency, exposure, the vulnerability of the elements and the value of the assets at risk.

Risk management, though not included in (Norsok Standard, 2001), considers risk assessment as its key element for the process. Identification of alternatives for risk reduction is the key stage in risk management process, which involves defining a different available sequence of actions or options. Risks associated with geohazards cannot be eliminated, but they can be managed. Hence, the primary focus of geohazard risk management is to find the most appropriate ways and establish a balanced synchronization between the people and geohazards. It also involves in the enhancement of the behavior and adaptive capacity of human beings by making a rational use of resources for the sustainable development. Along with this, geohazard risk management is also focused on achieving long-term attentions of humans for creating a balanced environment (Han et al., 2011).

Figure 4.3 shows a broader picture of risk management, which is drawn fon the basis of theoretical knowledge of risk assessment and risk management. A risk is identified through an assessment of sources of risk, elements at risk, vulnerability analysis and potential consequences. Decisions are to be made for managing that risk so as to bring it to an acceptable level. Hence, as seen in the diagram too, the particular risk of a geohazard is then managed by implementing different methods. Expert knowledge is required for making such decisions. However, various socio-economic aspects that are affected by risk are observed. The risk is monitored for chances of new risks to occur and their additional effects. The risk

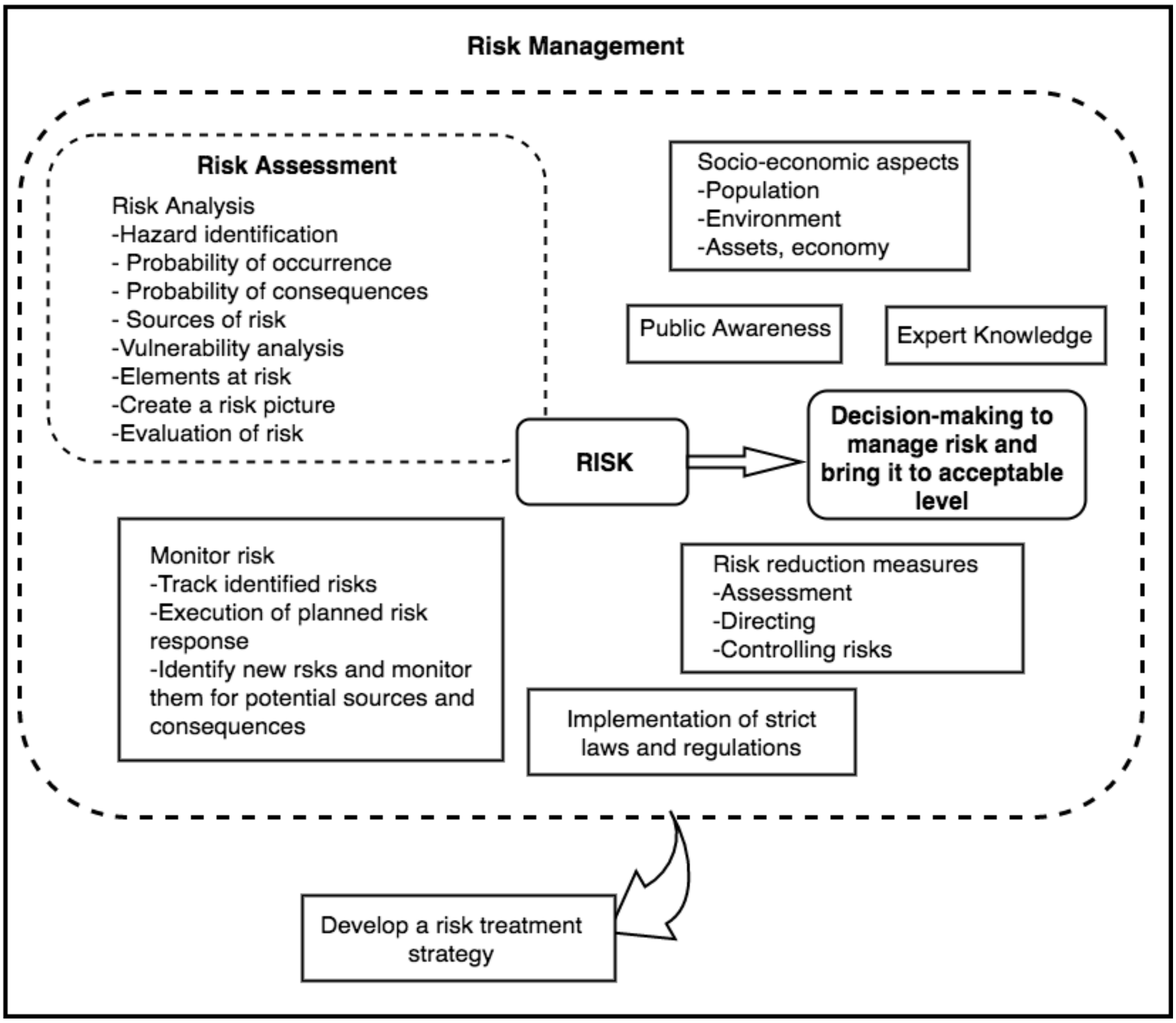

Figure 4.3: Risk Management Framework

is managed by various risk reduction measures like proper assessment, directing and controlling. Creating public awareness, and implementing strict laws and policies are also useful for the process. A risk treatment strategy is developed with a proper risk management.

4.3 Risk Assessment Matrix

The risk of geohazards can be analyzed by different methods. It can be quantitative risk analysis or qualitative or semi-quantitative risk analysis. Since the general case of geohazards is addressed, a qualitative risk analysis is chosen. For this, a risk assessment matrix is adopted. A risk assessment matrix is a tool that helps to evaluate risks qualitatively in terms of likelihood of occurrence of the events and the severity of their consequences (Thakur, 2015). It gives a quick overview of potential risks and thus, helps in making sound decisions regarding the priorities given for immediate supervision of dangerous situations, and in developing risk prevention strategies. We know that risk, in general, is a product of the probability of occurrence of an event and its probable consequences. i.e. **Risk = Probability × Consequences**. From this relation, it is seen that risk can be managed in two ways: either by lowering the probability of occurrence of an event (geohazards in our case) or by minimizing the probable consequences (loss of lives and damages to the environment). Geohazards are low probability and high impact events and lowering the likelihood of geohazard is a difficult task because of the uncertainties associated with it. Besides, one should also be aware of the secondary hazards that a geohazard can bring. It is useful to evaluate the triggering factors of geohazards and take necessary steps to reduce them. It helps to lower the probability of occurrence to some extent. Similarly, consequences can be minimized by better preparedness and response efforts.

Before constructing a risk matrix, levels of probability and consequence are defined. First, the probability or the likelihood of occurrence of geohazards is defined as:
Frequently: Occurrence probability 80-100%. The hazard is inevitable to occur.
Probably: Occurrence probability 50-80%. The hazard is likely to happen.
Occasional: Occurrence probability 50%. The hazard has both the 50/50 chances of occurrence and not occurrence. Cannot be ignored.
Remote/rarely: Occurrence probability 10-50%. The hazard has very low probability to occur but still can not be ignored.
Unlikely: Occurrence probability 0-10%. The hazard occurs in exceptional cases.

Similarly, consequence category is defined as:
Catastrophic: Enormous and long-term impacts. Greater number of fatalities and injured, Huge devastation, Damages of infrastructures and settlement, Enormous loss on economy, Requires longer time for recovery (may be several years), Huge cost for repair and reconstruction of structures, Coverage of greater extent of area, Very high severity
Major: Large impacts. Significant number of fatalities and injured, Recovery takes two to three years, Impact on economy, Huge damages of infrastructures, High severity
Moderate: Tolerable Impacts.
Minor: Acceptable Impacts.
Insignificant: Very fewer effects. Has no significant effect on human and environment

Table 4.1: Risk assessment matrix

Likelihood of occurrence	**Severity of Consequences**				
	Catastrophic	Major	Moderate	Minor	Insignificant
Frequent	High	High	High	Medium	Low
Probable	High	High	High	Medium	Low
Occasional	High	Medium	Medium	Low	Low
Remote	Medium	Medium	Medium	Low	Low
Unlikely	Medium	Low	Low	Low	Low

On the basis of this categorization, a risk assessment matrix is drawn as shown in Table 4.1. It requires a good understanding of geohazards, their occurrence probability and consequences to humans and environment for creating an effective risk matrix and then defining the risk. is a risk assessment matrix for geohazards.

Risk is classified as high, medium and low, as we can see in the risk assessment matrix. This classification has been done by considering the criticality of risk, how they should be addressed for drawing attention to safety on the future plans and on the basis of human acceptability level. They have been described in Table 4.2.

Table 4.2: Categorization of risk and their definition

Risk category	Description
High	The risk is entirely critical and unacceptable. They must be addressed with very high priority. A large number of fatalities and damages to structures and environment. A vast extent of destruction. Immediate measures must be taken for the reduction of risks and hazard mitigation. Rebuilding and rehabilitation take very long time, maybe several years.
Medium	The risk may be acceptable over a short term. Fewer fatalities and injured and considerable damages of structures and environment. No requirement of extensive resources but can be handled with a sound planning. Risk reduction and hazard mitigation plans must be included in the future strategies and budget plans.
Low	The risk is acceptable. No fatalities and only minor damages. Impose no any significant dangers. Can be ignored. Measures for the further reduction of risk and hazard mitigation must be implemented in conjunction with other security and mitigation upgrades.

4.4 Risk Acceptance Criteria

Once the risk of a geohazard is analyzed from the probability of its occurrence and the severity of its consequences, it should be evaluated for acceptance level. For this, we need to select risk acceptance criteria. However, selection of risk acceptance criteria is one of the most arduous tasks in risk assessment/ management (Kalsnes et al., 2010; Lacasse et al., 2012; Nadim, 2009). Acceptable risk is a level of risk that requires no further reduction and that society desires to achieve it easily (Kalsnes et al., 2010).

Risk acceptance varies from degree of risk and how humans perceive it. It also depends on preferences of people and the way they are given. So, in general, a risk acceptance criterion is a level to which one can bear the risks of a particular activity (geohazard in our case). Similarly, (Diamantidis et al., 2006) defines risk acceptance criteria by two methods: (i) Implicitly and (ii) Explicitly. Implicit measures involve safety in equivalence with other sectors. It means that a particular activity must impose risk levels at most equivalent to those imposed by another similar action. Explicit criteria tend to provide either as a quantitative decision tool or a comparable requirement. It is the human nature that they are more likely to accept risks of ordinary activities. For example people of Japan may have a different level of risk acceptance for earthquakes than those in Norway. Sometimes, risk acceptability is greatly influenced by experiencing some consequences of events. The existence of alternatives has also an enormous impact on the level of risk acceptance (Diamantidis et al., 2006).

When evaluating risks associated with geohazards, risk acceptance criteria can be defined from following questions.

- What is the risk category?
- What is the level of risk that one can sustain?
- How much risks are we able to take?
- What/How is your exposure to geohazards?
- What are the influencing factors in your existing environment?

Every individual bears a different level of risk acceptance according to their nature, experience, and the situation. For any geohazards, risk category can be distinguished by severity and likeliness of their occurrence (as shown in the risk matrix Table 4.1). When the context is about geohazards, it harms not only an individual but to the whole society or community or a nation. As an example here, we take landslide risk assessment. For this, (Diamantidis et al., 2006) have introduced a term 'collective risk', that moreover covers our situation. A collective risk is the total risk corresponding to the expected annual number of fatalities. That is;

$$R = \sum_{i=1}^{n} p_i . C_i$$

Where, n = Number of all independent and mutually exclusive accident scenarios i

p_i = Probability of occurrence of scenario i

C_i = Consequences of scenario i

F-N curves (N represents a number of fatalities, F the frequency of accidents/hazards with more than N fatalities) can be used as a guidance to what risk level a society is apparently willing to accept (Kalsnes et al., 2010; Lacasse et al., 2012; Nadim, 2009). The annual probability of causing N or more fatalities (F) to the number of fatalities, N is represented by these curves. Figure 4.4 is an F-N curve, which shows the acceptable and unacceptable regions. For a particular geohazard scenario, the consequences are plotted on the basis of the number of fatalities of that particular hazard versus the frequency of hazards with more than those fatalities. As a result, three levels of risks can be observed as; Acceptable Region, ALARP (Tolerable Region) and Unacceptable Region. The acceptable region is the one which has subtle impacts, and the risk is at acceptance level. The tolerable region is the one where the risks are higher than that of acceptable level but can be tolerated for a particular period. And the unacceptable region is the one with high risks that are beyond one's tolerability level. Such risks are mitigated through engineered and non-engineered techniques for future geohazards. The information provided by F-N curve is useful in carrying out further analysis and researches on risks of geohazards, such that those unacceptable risks can be brought to acceptable levels with possible effective measures.

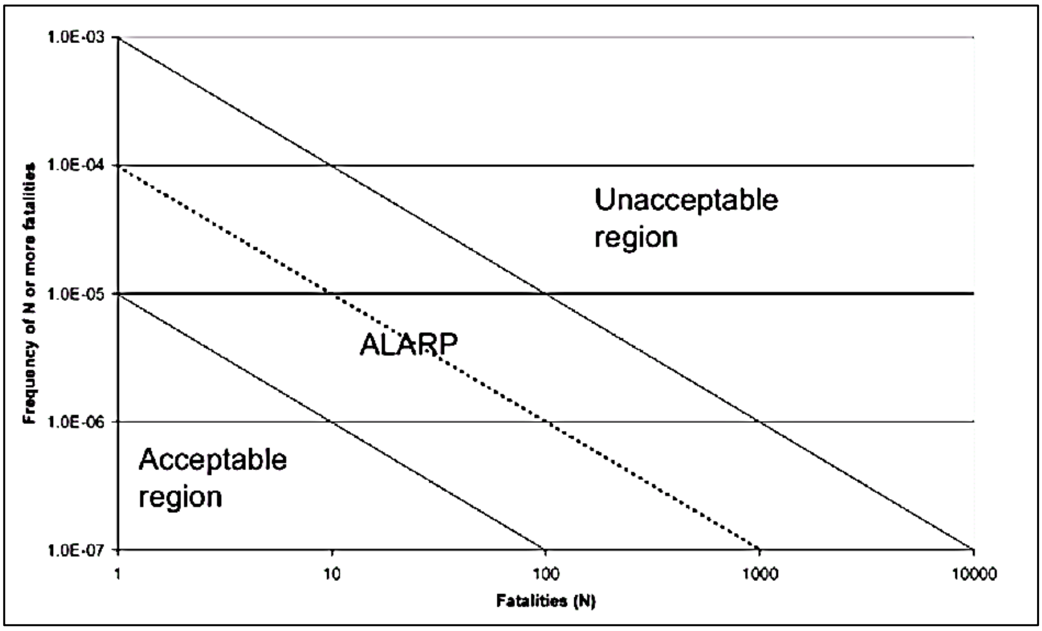

Figure 4.4: F-N curve (Diamantidis et al., 2006)

4.5 Uncertainties in Risk Analysis of Geohazards

Geohazards are natural phenomena, taking place with the changes in the geological features of the earth. Hence, the geology of any particular location plays a vital role concerning the hazards. Geology is a complex system consisting of various processes and changes occurring with the passage of time and conditions. The earth's surface faces various modifications with the varying weather and environment. The soil conditions, soil type, structure of the ground and hydrology are some of these factors of geology. Thus, one should be able to understand the earth sciences deeply for an accurate analysis of geohazards. Incomplete knowledge and poor understanding of any geological process result to the poor prediction of the geohazards and lead to various uncertainties.

Besides the natural conditions of the geological features, attention must also be paid for the possible presence of man-made materials on the ground (Rosenbaum & Culshaw, 2003). These materials include the engineering works, industrial processes, and waste disposal and so on, which affect the geological composition and features of the ground both directly and indirectly. In overall, the lack of proper knowledge about the geology and its processes and being unable to describe the whole geological phenomenon leads to uncertainties during the risk assessment of geohazards. Uncertainties not only prevent for an exact prediction of the occurrence of the hazards but also in the estimation of their probable effects. While we are evaluating the risks, we are not sure of the consequences of geohazards. Several uncertainties exist during the quantification of geohazards. As an example, when we are evaluating the risks of rock avalanches, we are uncertain about the probability and magnitude of future earthquakes (Solheim et al., 2005). These uncertainties make a huge difference in risk analysis as well as in planning the mitigation measures.

In geohazards, each of the elements at risk has their specific features. (Westen et al., 2006) mentions three basic features of these elements. They can be spatial, which relates to the items in relation to the position or location. The second feature is temporal, which refers to time; say population at a specified location. And the third one refers to thematic characteristics like the type of material the buildings are made up of or the age distribution of the population. These three qualities play a vital role as they pose particular characteristics in relation to the susceptibility and vulnerability to geohazards and creating several uncertainties in connection with their nature and existence.

Understanding the uncertainties associated with geohazards is not an easy task. One should have the knowledge about the difference between prediction and forecasting (Rosenbaum & Culshaw, 2003). Usually, it is the public, who expect prediction regarding the time, place, magnitude, and probability of a likely event, while most of the geoscientists can offer only improved forecasting about the future possibility. Also, geoscientists should manage that expectation by explaining the limits of their knowledge.

Two types of uncertainties are more relevant in geo-practice (Lacasse et al., 2012). They are:
(i) Aleatory Uncertainties and (ii) Epistemic Uncertainties
Aleatory uncertainties represent the natural randomness of a variable and cannot be reduced or eliminated. In the context of geohazards, it refers to the randomness in the physical properties of geological characteristics, objects, and processes. Epistemic uncertainties represent the uncertainty that arises due to the lack of knowledge on a variable. It includes mainly the uncertainty in measurement, statistics or the model (Nadim, 2007). Imperfections in the instrument used for assessing the geological inspection or inadequate methods for the registration of data causes measurement uncertainty. Earth is a big system with a broad range of geologic processes and changes, which are not understandable. Detailed information and data are also difficult to obtain. In such cases, the knowledge is often incomplete due to the lack of exact data or a low-quality data.

Risk assessment in these days addresses the uncertainties associated with geohazards and uses various tools to evaluate the losses with probabilistic metrics, expected annual loss and probable maximum loss (Lacasse et al., 2012). (Deck & Verdel, 2012) describe briefly about various uncertainties related to risk analysis of geohazards.

4.6 Decision-making under Uncertainties

During risk assessment of geohazards, one has to deal with various uncertainties that arise from limited knowledge about the geological processes causing hazards, errors in measurement of temperature or distance, incomplete observations, and variability in other parameters. Geohazards are high risks events with low probability and larger consequences, and uncertainties create a great challenge in decision-making process causing difficulty in predicting the possible outcomes of the decisions (Aven, 2008). A thorough assessment of the vulnerability of these aspects (people, assets, and the environment) in the premises of geohazards, provide some useful sustenance in making the decisions regarding the mitigation of consequences of geohazards (Rosenbaum & Culshaw, 2003). Since risks refer to the probabilities about what the implications of an event will be, they should be considered well during risk analysis. But probabilities are imperfect tools to express uncertainties (Aven, 2008). Hence, we need to look beyond probabilities for proper assessment of uncertainties, and this requires a good background knowledge. Probability theory and reliability analysis provide a rational framework for dealing with uncertainties and decision-making under uncertainties.

Bayesian network is a useful tool that provides an adaptable framework for expressing those uncertainties. It is a well-informed strategy for the scientists and decision makers for selecting sufficient forecasting variable for quantitative natural hazard assessments. No matter geohazards like earthquakes, tsunamis, snow avalanches or landslides have a broad range of differing causes, triggers and consequences; prediction of these hazards is something similar (Vogel et al., 2014). Bayesian networks are probability based graphical models, and they represent randomness and conditional dependency of any variable. It is usually represented as Directed Acyclic Graph (DAG). A complete use of Bayesian Networks for geohazards like earthquakes, floods and landslides have been discussed by (Vogel et al., 2014). Similarly, (Johnson et al., 2012; Straub & Grêt-Regamey, 2006) have made a detailed symposium on Bayesian framework for modeling snow avalanches.

In the situations of making decisions under uncertainties, one should be aware of the effectiveness of the decisions and look over to several alternatives because decision-making process is a difficult task and is often related to choosing between a set of options. An appropriate understanding of both the geological processes and geological changes is required for a proper assessment of possible uncertainties associated with geohazards. Consequently, vulnerability and exposure assessment and evaluation of elements at risk should be done. Considerations must be made for the uncertainties present, and hence, the best alternative should be chosen for making decisions on mitigating risks of geohazards.

5 Specifics of Landslides- Landslides in Nepal

Nepal has witnessed several geohazards in the last decades which include some major earthquakes and landslides (ADPC, 2010). Fragile geological conditions, diverse topographical features, high precipitation and deeply weathered rock materials have made the country vulnerable to different hazards. In addition to these factors, the socio-economic aspect of the country is also responsible for increasing the vulnerability to hazards. Every year, a significant number of people lose their lives and property by suffering from many large to small-scale hazards.

Landslides have been one of the major geohazards in Nepal. The primary causes of landslides in Nepal are classified into four categories (Dahal, 2012). They are:

(a) Geological causes (weak and weathered materials and difference in permeability of materials)

(b) Morphological causes (fluvial, slope erosion, tectonic uplift, erosion of marginal sides)

(c) Physical causes (extreme and prolonged precipitation, earthquake, and snowmelt)

(d) Human causes (deforestation, irrigation, mining, road construction, water leakage, changes in land use)

At recent, Nepal Earthquake 2015 was one of the major geohazards in Nepal, which not only caused an enormous consequence but also triggered several landslides and snow avalanches in different parts of the country.

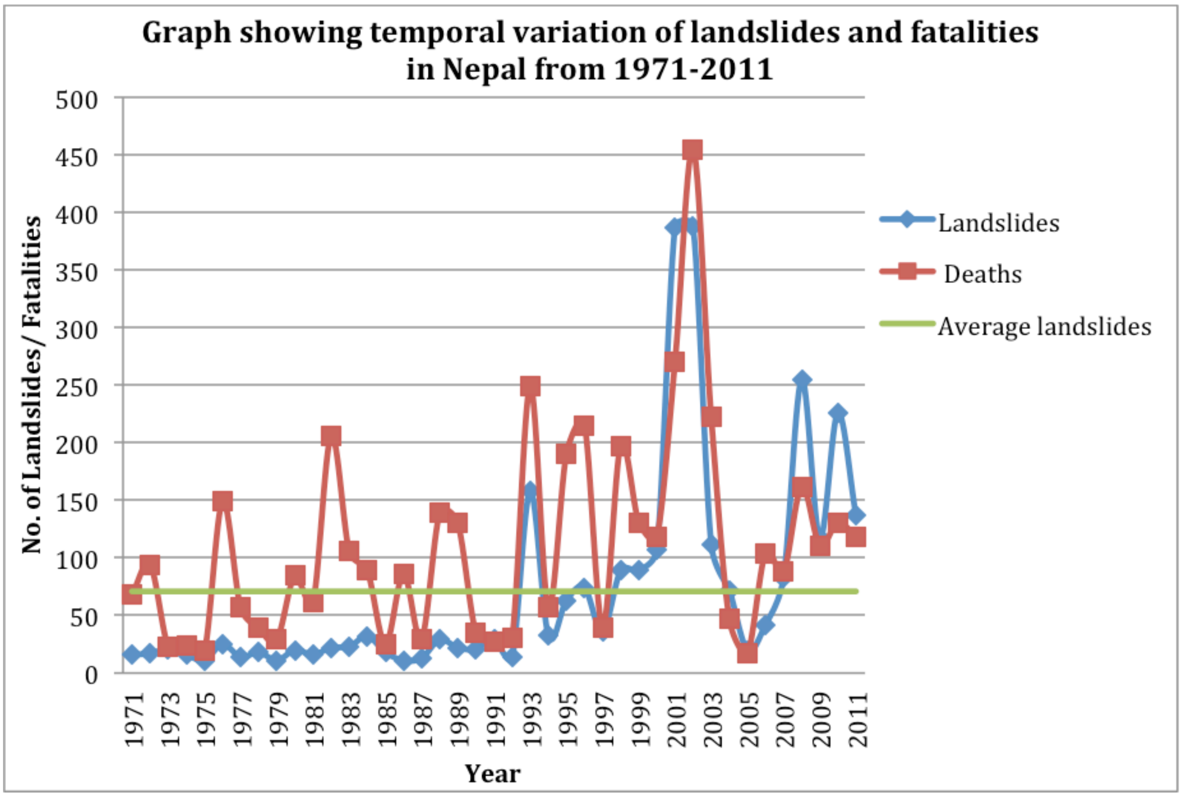

Figure 5.1: Graph showing temporal variation of landslides and fatalities in Nepal from 1971-2011 (Data Source: DIMS, 2011)

With the disaster data obtained from (DIMS, 2011), graphs have been plotted for the temporal and spatial variation of landslides for 41 years. There has been a total of 2908 landslides and 4476 fatalities in all over the country during this period. Figure 5.1 shows the total number of landslides and deaths on the basis of time.

Nepal is divided into five development regions and the occurrence of landslides varies accordingly along the country. Figure 5.2 shows the spatial variation in the total landslides in Nepal for a 41-year period.

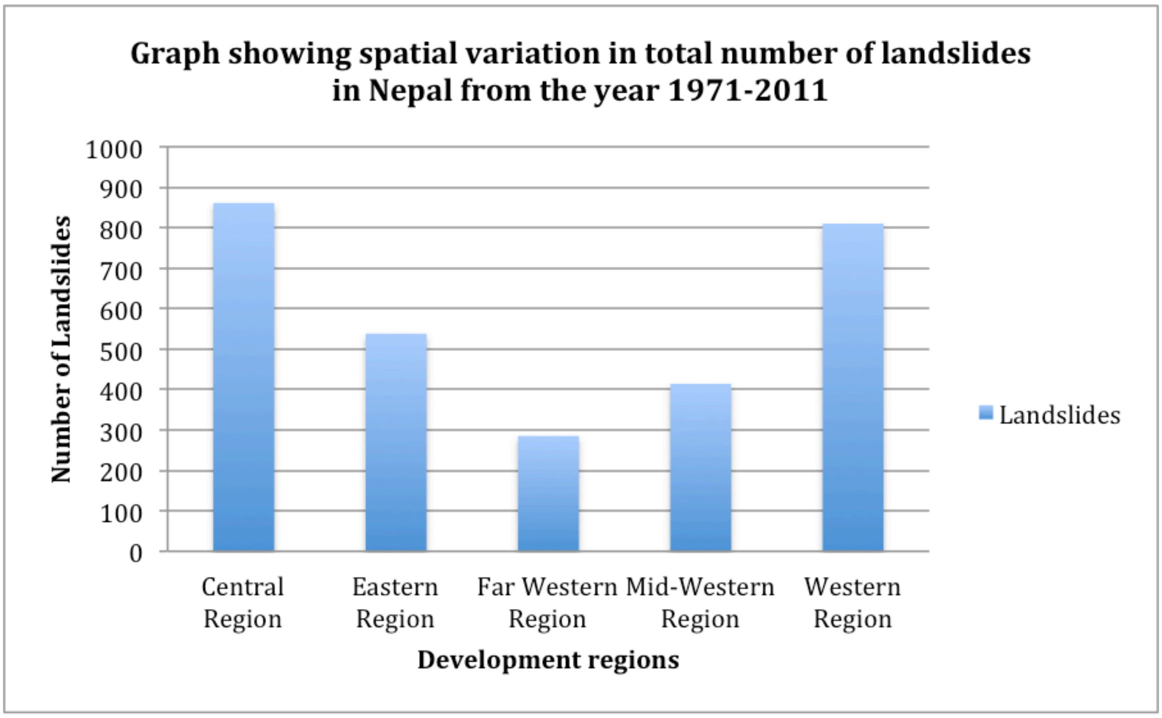

Figure 5.2: Graph showing spatial variation of landslides and fatalities in Nepal from 1971-2011 (Data Source: DIMS, 2011)

It is seen from Figure 5.2 that the Central region and the Western region of Nepal are more prone to landslides than the other regions. The geology, hydrology and various other factors have made this difference in the occurrence of landslides.

Landslides are usually initiated by two basic factors (Chalise & Khanal, 2001; ADPC, 2010); (a) Rainfall and (b) Earthquake. They are discussed hereunder following headings.

5.1 Rainfall-induced Landslides

Monsoon is the primary source of rainfall in Nepal, which lasts from June to September, causing an annual precipitation of approximately 80%. Landslide events are at their peak during these periods. But the duration and amount of rainfall (monsoon) vary across Nepal. The mean annual rainfall ranging between 1,500 mm and 2,500 mm prevails over most parts of the country (Dahal, 2012). However, the distribution of precipitation is not even, though there is heavy rain during monsoon. This unevenness triggers landslides in Nepal. Nepal faces several hundreds of landslides every year. According to (Howell, 2001), the soil is saturated during monsoons, which as a result of intense rainfall gets super saturated. At this point, the soil is at its lowest level of cohesion and has the maximum weight, ultimately leading to slope failure.

Rainfall induced landslides are more prevalent in hills and mountainous districts of Nepal (ADPC, 2010). As an example of such event, Figure 5.3 shows a massive landslide occurred in Mankha Village, Sindhupalchowk district of Nepal. The village lies at some 100 kilometers east of the capital Kathmandu. According to (Sharma, 2014), it left at least eight people dead and several hundreds of people missing. Besides this, the landslide blocked the flow of Sunkoshi River causing floods, which then wiped away several dozens of houses. Several older landslides' history can be found, from which, it is believed that mostly the rainfall on the older landslide zones, triggers the new landslides.

Figure 5.3: Massive landslide in Sunkoshi, Nepal (Sharma, 2014)

Uncontrolled and unsafe development activities like road constructions are very prevalent in Nepal. Deforestation is carried out for such purpose and also for settlement and agricultural purposes. Deforestation or the loss of vegetative cover results no longer existence of roots, thus, affecting the root-soil interaction and consequently causing slope instability. Such slopes are easily swiped away by the flowing water gullies during rain. As a result, the risks of rainfall-induced landslides increase.

Figure 5.4 shows the average monthly rainfall from year 1990 to 2012. We can see this increasing trend of annual rainfall during these monsoon seasons.

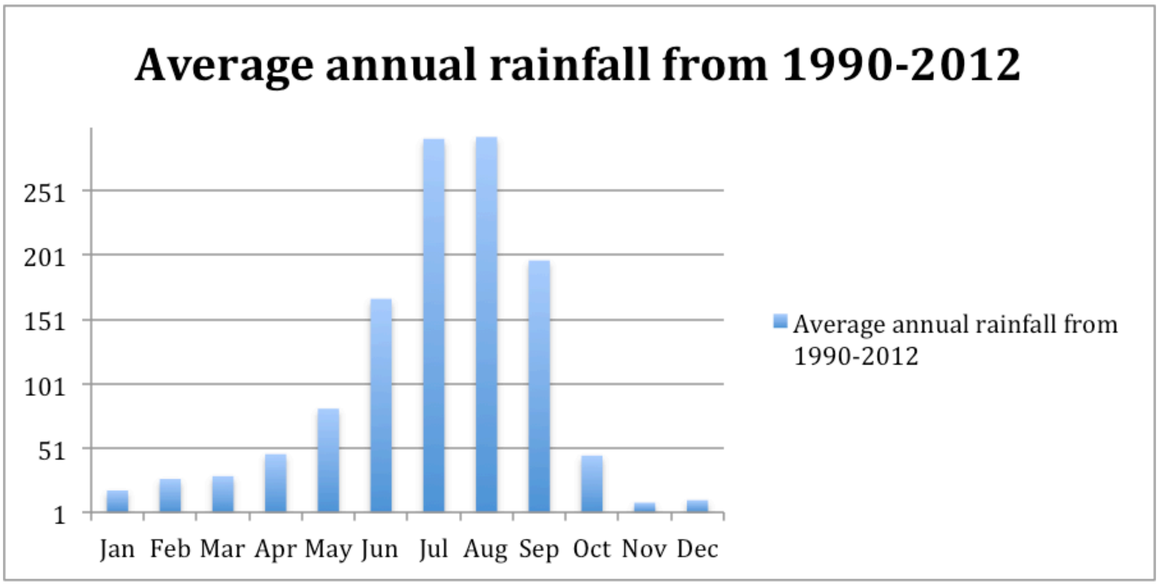

Figure 5.4: Graph showing average annual rainfall from 1990 to 2012 (CCKP, 2016)

5.2 Earthquake-induced Landslides

Nepal comprises of Himalayas that have been formed due to the collision of Indian Plate and Eurasian Plate at about 40 million years ago (Chalise & Khanal, 2001). With these plates converging to some inches every year, several earthquakes occur. Nepal earthquake 2015 was the biggest one at recent. According to USGS, these earthquakes trigger smaller to larger landslides in many parts of Nepal (especially on the hilly regions). They pose both immediate and long-term hazards to the villages and infrastructures within the affected areas. The overhanging slopes with loosely lined rocks and boulders fall with the shaking of the earth. Besides this, new earthquake-induced landslides also reactivate the older landslides, thus causing a massive catastrophe.

Figure 5.5: Hills at Rasuwa, Dhunche falling due to earthquake in Nepal (NDTV, 2015)

Figure 5.5 shows a landslide initiated in one of the hilly districts in Nepal due to the massive earthquake. Loose soil with less stable slopes is prone to landslides. Even a less tremor is sufficient to bring a slide. Despite the fact that the reasons behind landslides are many, deforestation is the major one.

5.3 Soil Bioengineering for Landslides

Soil bioengineering techniques are prevalent for preventing the risks of landslides in Nepal. It is a simple applied vegetation-based technique that uses comprehensive engineering practices in combination with integrated ecological principles (Dhital et al., 2013). It takes benefits of the specific biological and technical characteristics of natural vegetation alone, or in combined form with living or non-living structures. Consequently, it helps in the enhancement of ecological balance and maintaining slope stability. It is a cost-effective technique as it utilizes the locally available materials. Despite the involvement of engineering practices, the labor cost for bioengineering is also little, which makes it efficient and more useful in the developing countries like Nepal (Howell, 2001; Lammeranner et al., 2005).

Bioengineering has been practiced for a very long time in Nepal. These practices in Nepal against landslides include brush layering, palisades, vegetative stone pitching, live check dams and fascines. (Dhital et al., 2013) describes these methods in detail. Further, it points out that although the use of vegetation for protection and stabilization of slopes is on an increase, planting is usually carried out without explicit knowledge. People lack the knowledge regarding the way in which the plants will act to improve slope condition. They lack an understanding of which plant is suitable for which soil conditions and the role it plays in preventing landslides. A conclusion has been drawn by (Dhital et al., 2013; Howell, 2001; Lammeranner et al., 2005) that the majority of published literature is based on practical experience but not on the scientific research and data about conditions and modes of failure.
And hence, there is a need for more scientific research concerning the suitability and efficiency of soil bioengineering techniques. It is rather a challenging task to access each and every parameter affecting the suitability as well as the efficiency of soil bioengineering technique. Lack of precise data about the influencing factors and lack of specific methods to quantify these factors may be the principal reason for this.

5.3.1 Suitability of Bioengineering Techniques

Soil bioengineering methods currently used for preventing landslides have been brought into Nepal over the last 30 years (Lammeranner et al., 2005). Due to this reason, bioengineering is not a new topic to acknowledge. It involves the combination of vegetation-based engineering techniques. Nevertheless, its long practice, there lacks a scientific research regarding the suitability. The suitability of bioengineering techniques is dependent upon various factors. They are discussed hereunder:

5.3.1.1 Geological Features

Nepal has a diverse land feature from south to north. Of these, Siwalik (Sub-Himalayan) and Lesser Himalayan zones are more susceptible to landslides (Dhital et al., 2013). Siwalik region consists of an alternation of sedimentary rocks like mudstone, sandstone and conglomerate. Lesser Himalayan zone consists of low-grade metasediments including rocks like slate, phyllite, quartzite, limestone and dolomite. Slopes in Nepal with a variation in altitudes from 150 to 1500 m are fragile because of immature slope lands, high intensity of rainfall and deforestation (Dhital et al., 2013). Besides, both natural and engineered slopes having slope angles between 30^0 and 40^0 are highly vulnerable to landslides.

Land topography plays a significant role in deciding the appropriateness of any bioengineering technique. The growth of vegetation highly depends on altitude and the slope features like slope-facing (either towards south or north) because in Nepal, southward facing slopes receive plenty of sun than the northwards and are usually dry. Suitable bioengineering technique concerning the slope angle and slope length are discussed by (Howell, 2001). Table 5.1 shows some of the bioengineering techniques prevalent in Nepal at different slopes.

Table 5.1: Choice of bioengineering technique for various slopes, modified from (Howell, 2001)

Slope angle	Slope length	Material drainage	Site moisture	Technique(s)
> 45^0	> 15 m	Good	Damp	Diagonal grass lines
			Dry	Contour grass lines
		Poor	Damp	1. Downslope grass lines and vegetated stone pitched rills, or 2. Chevron grass lines and vegetated stone pitched rills.
	< 15 m		Dry	Diagonal grass lines
		Good	Any	1. Diagonal grass lines, or 2. Jute netting and randomly planted grass
			Damp	1. Downslope grass lines, or 2. Diagonal grass lines
		Poor	Dry	1. Jute netting and randomly planted grass, or 2. Contour grass lines, or 3. Diagonal grass lines
$30^0 – 45^0$	> 15 m	Good	Any	1. Horizontal bolster cylinders and shrub/tree planting, or 2. Downslope grass lines and vegetated stone pitched rills, or 3. Site grass seeding, mulch and wide mesh jute netting
		Poor	Any	1. Herringbone bolster cylinders and shrub/tree planting, or 2. Another drainage system and

				shrub/tree planting
	< 15 m	Good	Any	1. Brush layers of woody cuttings or 2. Contour grass lines, or 3. Contour fascines, or 4. Palisades of woody cuttings, or 5. Site grass seeding, mulch and wide mesh jute netting
		Poor	Any	1. Diagonal grass lines, or 2. Diagonal brush layers, or 3. Herringbone fascines and shrub/tree planting, or 4. Herringbone bolster cylinders and shrub/tree planting, or 5. Another drainage system and shrub/tree planting
$< 30^0$	Any	Good	Any	1. Site seeding of grass and shrub/tree planting, or 2. Shrub/tree planting
		Poor	Any	1. Diagonal lines of grass and shrub/tree planting 2. Shrub/tree planting
	< 15 m	Any	Any	Turfing and shrub/tree planting
	Base of any slope			1. Large bamboo planting, or 2. Large tree planting
Special conditions				
Any*	Any*	Any*	Any*	Site seeding of shrubs/small trees
$> 30^0$	Any	Any rocky material		Site seeding of shrubs/small trees
Any loose sand		Good	Any	Jute netting and randomly planted grass
Any rato mato (red clay)		Poor	Any	Diagonal lines of grass and shrub/trees
Gullies $\leq 45^0$	Any gully			1. Large bamboo planting, or 2. Live check dams, or 3. Vegetated stone pitching
Note: * Possible overlap with parameters described in the rows above.				

5.3.1.2 Soil and Climatic Conditions

The growth of a plant is dependent on both the soil and climatic conditions. Roots are regarded as the primary contributors for increasing slope stability. However, the type of soil and the factors present in the soil influences their growth. A good soil structure usually comprises of sufficient pores between its particles that allow water and air to enter quickly. It has a good drainage system as well as it holds adequate moisture and mineral contents required for the healthy and proper growth of a plant. Hence, depending upon the type of soil, plants with specific root systems should be selected. Soil holds biological, chemical and hydrological properties that influence the growth of a plant. Biological properties refer to the presence of microorganisms and humus content. The chemical factors are the pH of the soil, soil temperature, amount of nitrogen and the availability of essential nutrients for plant growth. The hydrological factors include moisture content in the soil. The appearance and depth of root system depend on the type of soil. Suitability of bioengineering technique is thus liable on the nature of the soil and some essential nutrients it contains for a plant growth.

A soil test is required for ascertaining the suitability of soil bioengineering. The soil should be tested for the suitability of the growth of a plant variety. Also, it must be tested for the strength parameters like cohesion, compression, shear, the angle of friction, etc. Nepal consists of infertile soil in most of the forests. According to (Howell, 2001), this infertility has been caused due to the young, unstable terrain and the weathering and leaching properties of the monsoon. Soil infertility has a great impact on the growth of vegetation as well as on the implementation of bioengineering techniques. Measures should be taken to improve soil quality. Accordingly, a suitable bioengineering technique must be used.

In the context of Nepal, the climate varies from tropical to the arctic within the 200 km span from south to the north. While the issue is on landslides, landslide-prone regions, Siwalik Hills have tropical to sub-tropical climates and the Lesser Himalayas have a diverse environment. It is sub-tropical in valley bottoms, warmer on valley sides and cool temperate on higher ridges. Mean temperature remains around 15 ^{0}C and usually increases from north to the south. It decreases with elevation and drops by 6.5 ^{0}C per 1000m. Nepal receives almost about 1500 to 2500 mm rainfall in a year. Rainfall occurs due to southeast monsoon lasting between June and September, which contributes to about 80% of the total annual precipitation (Dhital et al., 2013).

As landslides in Nepal are triggered mainly by rainfall, prevention activities should be carried out before the monsoon. Bioengineering works are carried out in the pre-monsoon period (Dhital et al., 2013). However, there is a need to understand the benefits of implementing such techniques correctly before the monsoon. It gives time for proper growth of the plant and development of its root structures so that they can be able to function properly.

5.3.1.3 Selection of the Best Technique

Carrying out a thorough site investigation helps in selecting the best technique of soil bioengineering. It is essential to look at the slope properties before choosing a method. If the existing slope is longer than 15 m, then there may be a danger of surface scour. In this case, some physical scour check like wire bolsters should be used. Similarly, if the slope is made up of poorly drained material with relatively high clay content, problems of shallow slumping has to be faced. In such a case, a bioengineering technique that also includes a proper drainage system can be useful. An observation of the site and its surroundings and carrying out some site investigations is necessary before implementing any technique (Howell, 2001).

Also, the sites which may require a combination of techniques should be investigated. The design of any technique must be site-specific, relying on the nature of the slope, soil characteristics, climatic factors and efficiency of that technique for preventing landslides. An initial assessment of landslide-prone slopes can help in choosing the appropriate method of soil bioengineering. Various observations made by an initial evaluation of slopes and their feasible solutions are listed in Table 5.2.

Table 5.2: Initial Assessment of sites and their probable solutions, modified from (Howell, 2001)

S.No.	Site conditions	Solutions
1.	A very long, steep site and in danger of a massive failure below the surface	Retaining walls (To break the slope into smaller, more stable lengths)
2.	Foot of the slope undermined, threatening the whole slope above	Construction of Toe walls
3.	Distinct overhang or boulders supported by a soft, wording band	Construction of Prop walls
4.	Slopes made up of mostly hard rock, so that planting of nursery stock would be impossible	Direct seeding
5.	Rough slope covered in loose debris having locally very steep or overhanging smaller sections	Trimming of smaller sections/slopes

5.3.1.4 Selection of Plants

Vegetation is used in soil bioengineering to reinforce and stabilize the slopes. They carry a high function of sustaining biodiversity and giving a very positive influence on the ground structure and the whole ecosystem. They create a balance between the soil and water. Vegetation, when combined with several engineering structures for bioengineering, they perform both the structural and engineering functions to maintain the slope stability. The success of any soil bioengineering techniques depends heavily on the selection of the most appropriate plant species because all plants cannot perform the functions of bioengineering technique. These particular functions are defined by (Gobinath & G.P., 2014) as:

1) Armoring- Acts as an armor and prevent soil movement.
2) Catching- Helps to prevent debris flow and soil movement.
3) Draining- Helps in the efficient drainage of stagnant water and also during rainy seasons.
4) Supporting- Supports the subsoil from lateral movement.
5) Reinforcing- Increases the shear strength of soil.
6) Anchoring- Helps in anchoring the soil particles tightly.

The functions as mentioned above are performed by the roots of the plants. Hence, selection of best plants for soil bioengineering technique should be such that they have enough root strength, have high abundances, more likely in the local or surrounding areas and, adjustable

and suitable to the climatic conditions of Nepal. Usually, the combination of *Shorea robusta* and grassland is common on the lower slopes of Siwalik Hills (Dhital et al., 2013).
Plants with different root systems can be collected, and their roots can be evaluated for root density, specific gravity and strengths. It will help in selecting the best suitable plants for bioengineering. It also helps in the identification of appropriate species of plants for this technique and increases their practical usage. The tensile strength of roots and their ability to penetrate deep into the soil depends on the type of the root. Hence, the plant selected for bioengineering should have a good root system that they should be able to hold the soil firmly and also perform the functions mentioned above efficiently. Apart from this, root to shoot ratio (R:S) must also be studied because both of their existence hold a close relationship (Gyssels et al., 2005). Such a ration shows the balance between these two parts of the plants. The ratio depends on the stages of the plant development, growth conditions, kind of plant and the existing climatic and environmental conditions. The pattern and size of root systems have a significant influence in soil bioengineering.

Plants selected for bioengineering should be such that they serve the purpose both technically and economically. Therefore, selection must be made on the basis of their growing and surviving capacity, and their ability to perform the bioengineering functions. Plant species should be able to grow healthy even in harsh conditions or in the site's available soil and climatic circumstances, and be able to propagate quickly. Thus, it is very crucial to understand the ability of plant species for performing all the functions before using them for soil bioengineering.

5.3.1.5 Economic Aspects

A soil bioengineering technique must be such that it should be economically sustainable. The economic aspects of bioengineering are measured on the basis of the price of materials and manpower. It also includes the cost of transport of materials as well as construction.

Bioengineering has been known to be an economical technique for the prevention of landslides. It can be made more economic with a thorough research on the plants. Consequently, local plants can be selected, which possess all the fundamental characters of bioengineering functions. The choice of the best type of soil bioengineering technique for the available site and slope conditions should be made.

Community participation also plays a great role in making the soil bioengineering technique an economic one. It is also considered as a key to success for ecosystem re-establishment (Dhital et al., 2013).

5.3.2 Efficiency of Bioengineering Techniques

Despite the fact that bioengineering techniques have been practiced for so many years, accurate quantification of the associated factors is not done correctly. No précised formula or method can measure its efficiency. So we can look on to several factors which directly or directly affect its effectiveness. Moreover, suitability and efficiency of soil bioengineering technique are influenced by similar factors. They are discussed under following sub-headings.

5.3.2.1 Survival and Growth Rates of Plants

The success and efficiency of a bioengineering technique are highly dependent on the survival and growth rate of the plants. As bioengineering is a vegetation-based engineering technique, the life, and longevity of this method is almost entirely dependent on the survival and growth rate of the vegetation. Pre-mature plants are easily washed away by the monsoon (Lammeranner et al., 2005). Therefore, the plant should be planted in appropriate environmental conditions such that they can survive quickly and grow well.

5.3.2.2 Selection of the Best Technique and Best Plants

Selection of best technique and selection of best plants for soil bioengineering are the most crucial factors for not only suitability of bioengineering technique, but also they help to measure the efficiency of soil bioengineering technique. The best technique and the best plants are those, which match with the available site conditions, slope and altitude conditions, soil and climatic features, and perform their functions efficiently.

5.3.2.3 External Intervention

Implementation usually comes with protection so as to increase its longevity and efficiency. However, several interventions come up with time and the changing environmental situations. In the context of Nepal, deforestation is the primary reason behind landslides. Besides, people living in hilly regions rare cattle like goats and sheep, which are left on the hills for grazing. Consequently, they harm bioengineering practices by feeding on available plants and damaging the built structures. In some of the cases, people are also responsible for destroying it as they rely on forests for grazing their cattle or for any other agricultural purposes. As a result, the efficiency of bioengineering technique goes decreasing with these interventions. Such responses should be minimized (to some extent) by implementing strong laws and regulations regarding a proper use of forests and their conservation. Community forests can be established where public contribute for growing plants and can collect fodders for their cattle and subsequently, conserve them too. Public awareness is also necessary for this context concerning the effects of landslides, and their prevention by implementing soil bioengineering. Here, both the government and community people play a significant role.

5.3.2.4 Root-soil Reinforcement

Since, soil bioengineering involves the planting of vegetation in combination with engineering techniques, a well understanding of the relationship between roots and soil is essential for both the selection of best plants, and increasing the efficiency of this method. Roots and soil carry out an integral role in improving the stability of the slopes and preventing landslides to a vast extent.

The soil exerts shear strength which is a property of measuring the cohesiveness and resistance of soil to the shearing forces exerted by gravity, moving fluids and mechanical loads. The soil is strong in compression but weak in tension; while plant roots are weak in compression but stronger in tension (Gyssels et al., 2005). When soil and roots are combined, a matrix is formed which is much higher in reinforcement. If the driving forces exceed the resisting forces in a slope, then landslides occur. However, a Mohr-Coulomb failure criterion is established to calculate this root-soil composite shear strength (Gyssels et al., 2005; Steinacher et al., 2009; Ziemer, 1981).

The maximum shear strength os soil is given by:

$$S = (C' + C_r) + (\sigma - \mu)\tan\phi'$$

Where, S= Maximal shear strength (or shear stress at failure) (Pa)

C' = Effective soil cohesion (Pa)

Cr = Root cohesion (Pa)

σ = Total normal stress or shear stress (Pa)

μ = Pore water pressure (Pa)

ϕ' = Angle of effective shearing resistance or angle of effective normal friction (^{0})

Root cohesion holds a relationship between the total tensile strength of roots and the areal density and root distribution. As given in (Gyssels et al., 2005), the equation is:

$$C_r = T_r \left(\frac{A_r}{A}\right) (\cos\beta \tan\phi' + \sin\beta)$$

Where, C_r = Root cohesion (Pa)

T_r = Total tensile strength of roots, accounted for different diameters (Pa)

A_r = Area occupied by roots (m^2)

A = Soil cross section considered (m^2)

β = Shear distortion from vertical (^{0})

ϕ' = Internal angle of friction of soil (^{0})

Furthermore, the term (cos β tan ϕ' + sin β) being relatively insensitive to the changes in shear distortion is close to numerical value 1.2 for a large range of angle of internal friction. Hence above equation can be re-written as:

$$C_r = 1.2T_r \left(\frac{A_r}{A}\right)$$

From this new equation, root cohesion is seen to be dependent directly on the overall tensile strength of roots and the root area ratio. Consequently, the maximal shear strength increases as these parameters increase.

An appropriate understanding of all these parameters helps to understand root-soil interaction which leads to the choice of the best plants for bioengineering. Here, the best plants refer to those having a particular root system and contribute highly to increasing the shear strength. The effect of root reinforcement depends on the morphological characteristics of the root system, diameter, and the strength of individual roots. It also depends on the concentration of the roots, the tensile force of each root, soil-root cohesive strength and the distribution of the root system in the soil. Plants possessing good root system and holding a proper interrelationship between their roots, and the existing soil increases the strength as well as longevity of any bioengineering technique. Accordingly, it increases the efficiency too.

5.3.2.5 Role of Vegetation on Increasing Slope Stability

The efficiency of bioengineering techniques increases with the passage of time because of maturity and a good establishment of the vegetation. Most of the people in Nepal do have the knowledge that landslides occur due to deforestation or any other reasons, and they also know that planting vegetation can help in protecting and stabilizing the slopes. But they are ignorant about the science behind how plants act to improve the slope conditions.

Slope stability carried out for preventing landslides is driven by two major properties of natural vegetation. They are (a) Mechanical and (b) Hydrological (Ali et al., 2012; Dhital et al., 2013). The mechanical property of plant roots on slope stability is mainly endorsed for increasing the shear strength of the soil (Dhital et al., 2013). Roots form a network-like structure underneath the ground that binds and anchors the soil. This effect thus increases shear strength. (Steinacher et al., 2009) explain the mechanical reinforcement of roots by three ways. (a) Anchoring, (b) Lateral support by crossing zones of weakness and, (c) Acting as long fibrous binders within a weak soil mass. Similarly, the hydrological property includes the processes like interception, precipitation, evaporation, storage, leaf drip, pool formation, water uptake, transpiration and infiltration. Hydrological effects according to (Ali et al., 2012), involves the removal of soil water by evapotranspiration through vegetation.

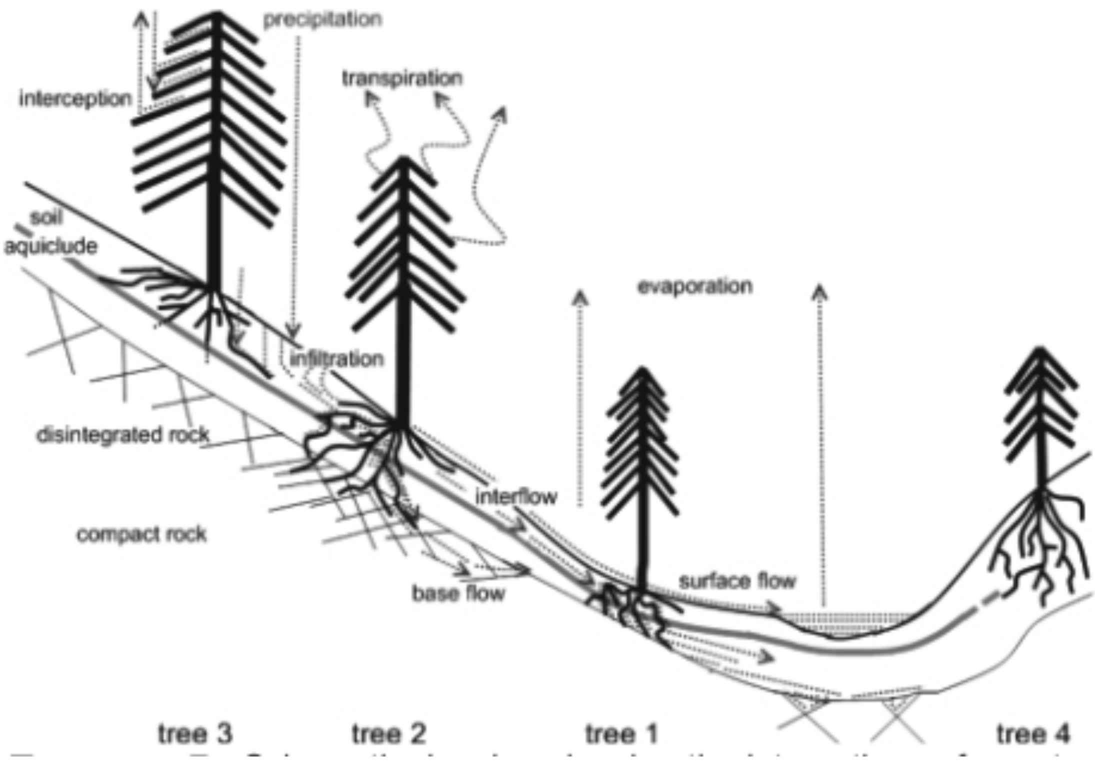

Figure 5.6: Interaction of vegetation, soil, rock and water (Steinacher et al., 2009)

It leads to an increase in the ground suction or reduction in pore water pressure, subsequently increasing the shear strength of the soil. Besides, reduction in moisture content due to evaporation by plants also reduces the weight of the soil mass. In overall, these properties contribute significantly to maintaining slope stability. Hydrological processes (as also shown in Figure 5.6) involved in this phenomenon are explained briefly by (Prandini et al., 1977).

Figure 5.6 as adapted from (Steinacher et al., 2009) illustrates these properties and the interactions of vegetation, soil, rock and water. Four trees located at different conditions of a slope and soil and their effects on stability are also discussed. As observed in Figure 5.6, these interactions and their effects on Stability for each cases of trees are explained in Table 5.3.

Table 5.3: Possible interactions between tree roots and soil with effects on stability, modified from (Steinacher et al., 2009)

Type	Description	Effect on Stability	Effects on friction angle (when saturated with water)	Chances of Landslide
Tree 1	Tree with many roots Thin soil cover with hard rocks beneath, and is difficult to penetrate	Low	Decrease	High
Tree 2	Similar conditions to Tree 1, but slightly fragmented rocks that can be penetrated by roots	Very High	Decrease	Minor
Tree 3	Medium to thick soil cover, not reaching the zone of fragmented rocks, Slope has greater friction angle	Medium	Decrease	Likely
Tree 4	Soil cover thicker than tree root length, No contribution to mechanical effects of roots	Low	Decrease	Likely

(Howell, 2001) has discussed about major mechanical and hydrological mechanisms of vegetation and their effects on slope stability. They are shown in the Table 5.4.

Table 5.4: Major effects of vegetation on slope stability, modified from (Howell, 2001)

S.No.	Mechanical mechanisms	Effect	S.No.	Hydrological mechanisms	Effect
1.	Roots reinforce the soil and increase soil shear strength.	B	1.	Foliage intercepts rainfall causing absorptive and evaporative losses that	NA

				reduce rainfall available for infiltration.	
2.	Tree roots may anchor into firm strata providing support to the upslope soil mantle through buttressing and arching.	B	2.	Roots and stems increase roughness of the ground surface and permeability of soil, leading to an increased infiltration capacity.	A/B
3.	Weight of trees surcharges the slope by increasing normal and downhill force components.	A/B	3.	Roots extract moisture from the soil, which is lost to the atmosphere via transpiration, leading to lower water pressures.	NA
4.	Vegetation exposed to wind transmits dynamic forces into the slopes.	A	4.	Depletion of soil moisture may accentuate desiccation cracking in the soil, resulting in higher infiltration capacity.	A
5.	Roots bind soil particles to the ground surface and reduce their susceptibility to erosion.	B	5.	Lines of vegetation affect runoff and infiltration, depending on the surface micro-topography.	A/B
A=Adverse effect B= Beneficial effect NA= Not applicable in Nepal					

From this discussion, we understand the exact role that a plant plays for creating a balance in nature and also in preventing slope instability. A conclusion can be drawn that combination of both the hydrological and mechanical effects of a plant helps to improve the factor of safety. It is essential to understand the mechanisms of plant and its role in increasing slope stability to make the technique more efficient.

6 Risk Analysis of Landslides in Nepal

6.1 Landslide Hazard Assessment

A methodology (as shown in Figure 6.1) derived by NGI (ADPC, 2010; Kalsnes et al., 2010) is generally used for landslide hazard assessment in Nepal. Landslide hazard is estimated by an approximate combination of triggering factors and susceptibility factors. As triggering factors, we have extreme rainfall and earthquakes. Similarly, susceptibility factors are the slope, lithology, vegetation cover and soil moisture. Hazard maps are created concerning the triggering factors. A combination of hazard maps and the identification of elements at risk and vulnerable groups help to prepare risk maps.

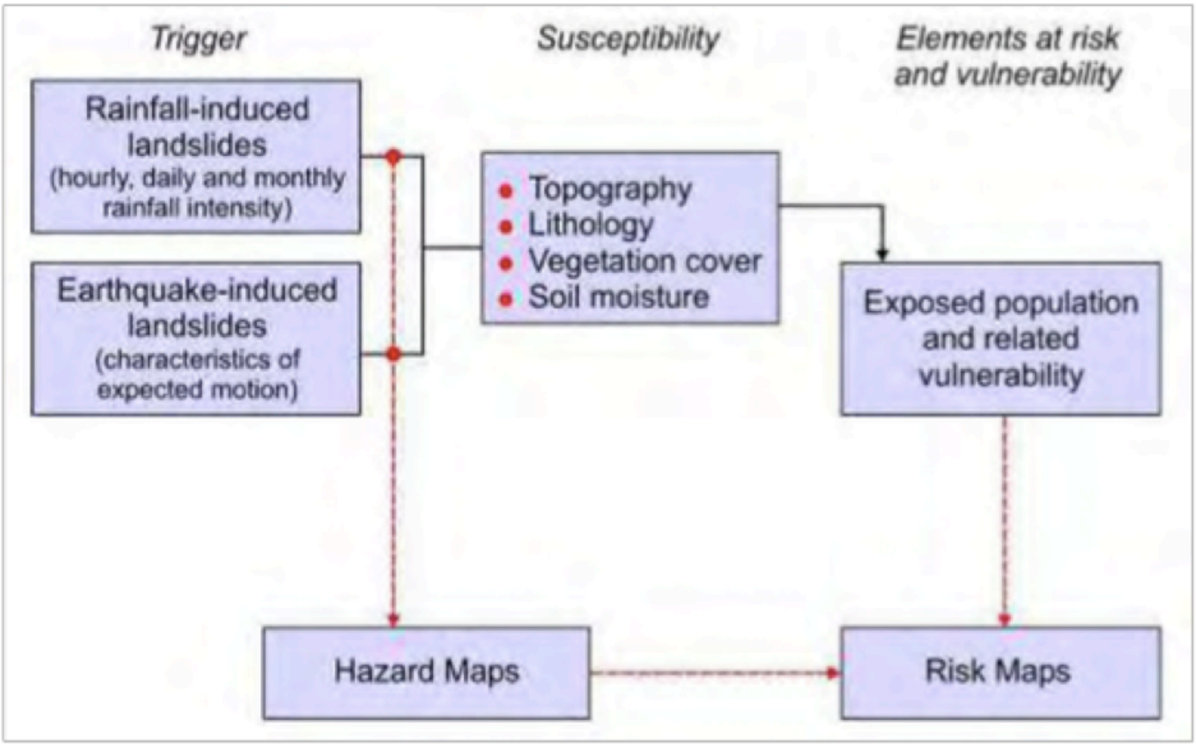

Figure 6.1: Schematic approach for landslide hazard assessment (ADPC, 2010)

Landslide events are usually high throughout monsoon in Nepal. During these months, precipitation is at its peak. However, we also need to look closely at the susceptibility factors as they have a great impact on the occurrence of landslides. Deforestation is one of the biggest problems in Nepal, which causes loss of significant land covers and consequently affecting the hydrological and mechanical properties of plants. It leads to a larger number of landslides mainly during monsoon.

Landslide hazard studies can be done by using susceptibility maps. It is a useful tool that helps to estimate the potential chances of landslide occurrence in the nearest future. (ADPC, 2010) has prepared two susceptibility maps for rainfall-induced and earthquake-induced landslides in Nepal for the assessment of landslide hazard as shown in Figure 6.2 and Figure 6.3 respectively. From these maps, a considerable variation in area coverage and probability

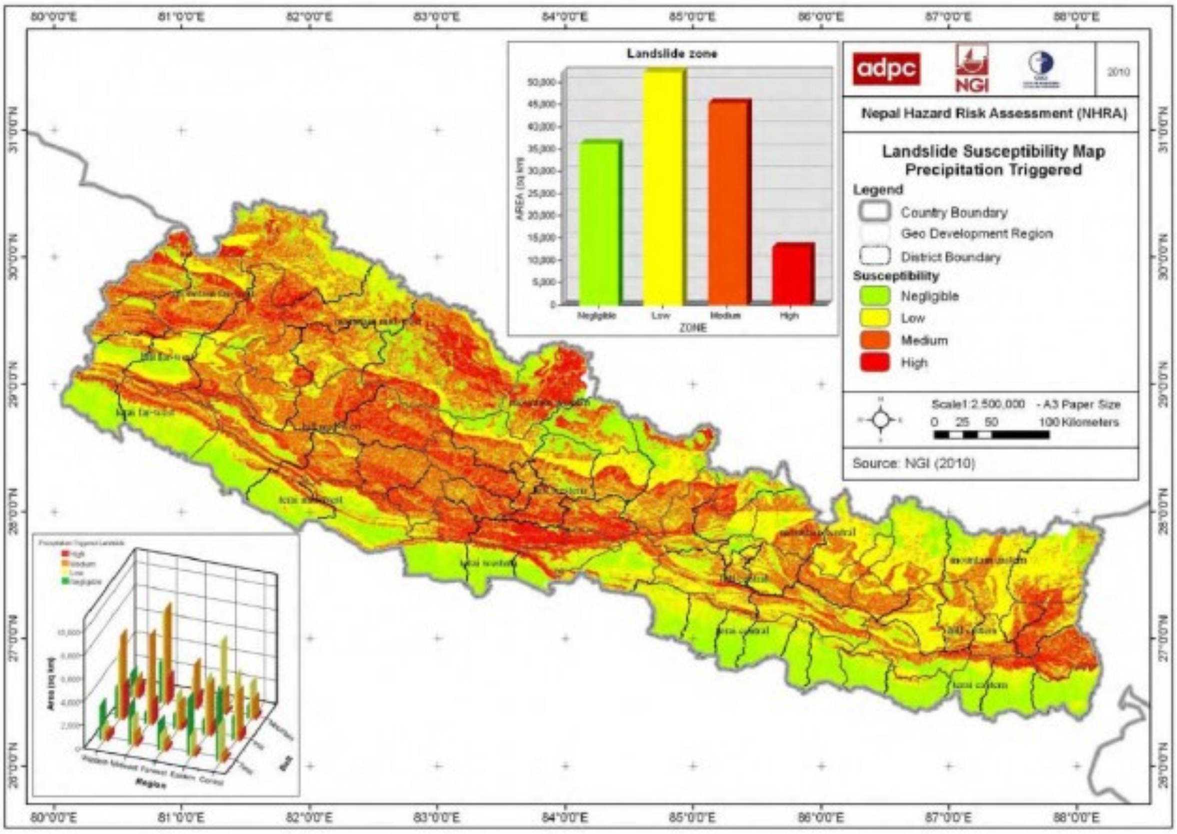

Figure 6.2: Landslide susceptibility map- Rainfall triggered (ADPC, 2010)

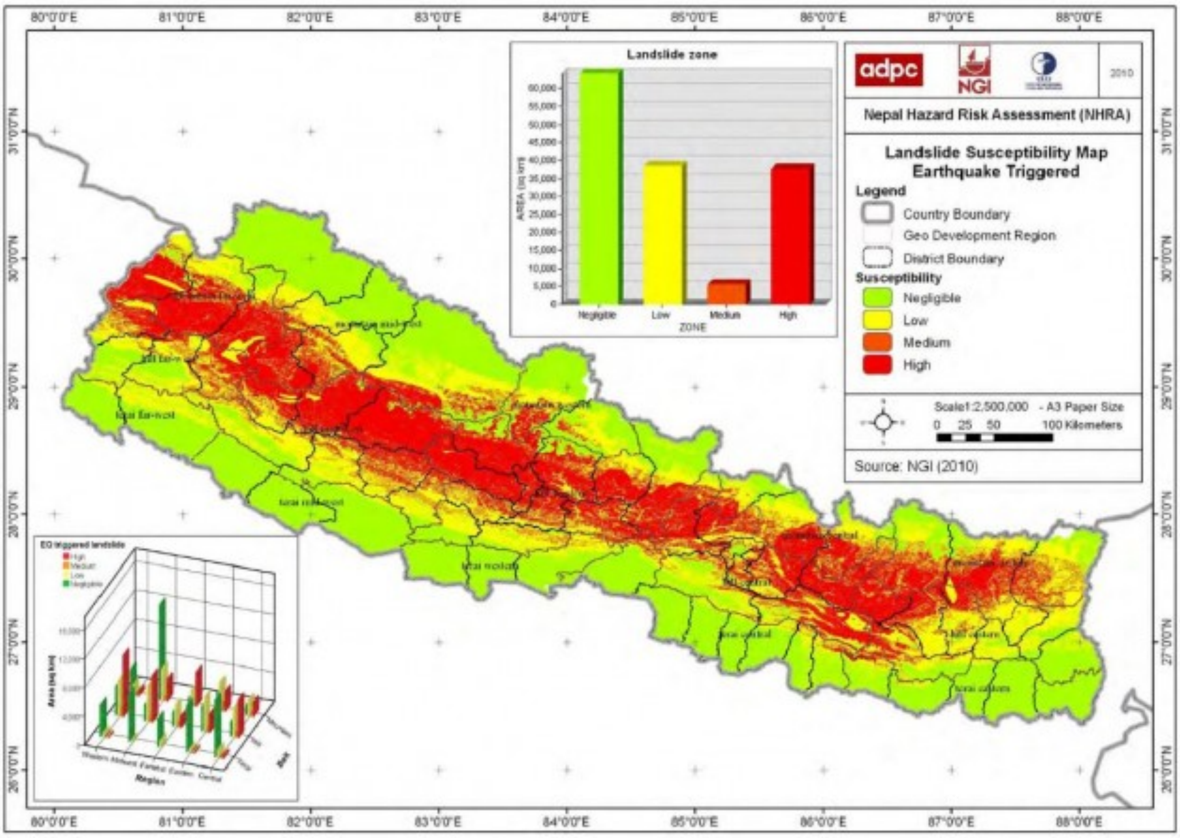

Figure 6.3: Landslide susceptibility map- Earthquake triggered (ADPC, 2010)

distribution can be seen in both the cases of landslides. Low and medium chances of rainfall-induced landslides can be observed in most of the regions of Nepal (refer Figure 6.2). However, the probability of landslide occurrence is very less on the southern parts because the areas of the south receive very less amount of rainfall in comparison to the northern parts. We can also see that the eastern regions of Nepal are less susceptible to rainfall-induced landslides than the western parts.

From Figure 6.3, we see that the middle hilly areas are highly vulnerable to earthquake-induced landslides. Medium severity zones cover very less geographical area and are situated in the surroundings of highly sensitive regions. Areas with small chances of earthquake-induced landslides have similar land coverage to that with high probability. The lowermost southern regions and uppermost northern geographical regions of Nepal have very low probability and cover wide area.

However, various limitations are associated with these maps. According to (ADPC, 2010), it requires a monitoring of continuous rainfall which is not always possible, and all regions of Nepal does not possess enough equipment and resources for this purpose. Similarly, the land use and land cover also play a vital role in developing hazard maps. The increase in deforestation and improper land uses have a direct impact on land cover. Such an issue should be taken seriously and addressed by possible means. Nepal, being a developing country, lacks advanced tools and techniques and has a limited availability of resources for rainfall monitoring, collection of data, landslide events data and fatalities data. It is likely to cause a significant difference in creating reliable hazard maps. Furthermore, (ADPC, 2010) points out to reduced awareness and interests of both the authorities and the general public about the risk of landslides. The primary reason behind this is the lack of knowledge regarding the firm correlation between landslides and other geohazard triggers. It has lead to an underestimation of the socio-economic impacts of landslides too.

6.2 Qualitative Risk Analysis

Qualitative risk analysis is a subjective evaluation of probability and consequences of any event. It comprises of prioritizing the identified risks by using a pre-defined likelihood and impact ranking scale. Here, in our case, this method is used for analyzing the landslide risks in Nepal. A rating scheme was created to evaluate the relative likelihood of landslide and the consequences in the form of scores. They were defined following their nature as in Table 6.1 and Table 6.2 respectively. Various triggering factors of landslides were identified on the basis of several published literatures and from (Chalise & Khanal, 2001; Dhital et al., 2013, Lammeranner et al., 2005).

An online questionnaire survey (Refer Appendix) was carried out in a group of 30 Nepalese having backgrounds from civil engineering, geology and environment. The analysis was based on the best possible knowledge. It added additional information in creating a typical picture of landslide risk. The survey was carried out in order to analyze the knowledge and perception of different people regarding the landslide hazards. It helped to discover the knowledge gap that people have in understanding various factors of landslides.

Probability ranking is classified as in Table 6.1 for occurrence of landslides in Nepal.

Table 6.1: Probability classification for landslides

Classification	Probability	Definition
1	Very unlikely	More than 80% chances of landslide occurrence
2	Unlikely	50-80% chances of occurrence
3	Occasional	50/50 chances of landslide occurrence
4	Likely	10-50% chances of occurrence
5	Frequently	Less than 10% chances of occurrence

Similarly, Table 6.2 shows categorization of consequences of landslides and impact definition.

Table 6.2: Categorization of consequences and impact definition

Ranking	Significance	Impacts
I	Insignificant	No effects
II	Minor	Very less impacts, acceptable but can not be ignored
III	Considerable	Tolerable impacts
IV	Major	High impacts, Unacceptable, Areas highly affected by landslides
V	Catastrophic	Critical effects, Unacceptable, Enormous impacts

An evaluation of these factors was done for possible risk mitigation measures. Table 6.3 gives a summary of identified triggering factors of landslides in Nepal. To each of these factors, a degree of probability was provided as described in Table 6.1 on the basis of how they contribute to initiate landslides. Similarly, a consequence category was also given regarding the extent of impacts that these factors bring with landslides. The ranking was done using the best possible knowledge. However, this ranking differs on one's knowledge and understanding about the factors and the phenomenon. With this risk ranking (ranking of probability and consequences), priority for minimization of triggering factors, and prevention and mitigation strategies for landslide hazards can be formulated in the nearest future.

Table 6.3: Summary of identified triggering factors

S. No.	Triggering Factors	Probable consequences	Probab-ility of landslides	Consequence Category	Risk Mitigation Measures
x1.	Soil structure/type	Impacts on stability of	3	V	• Analysis of risk zones

	and slope alignment	slope as well as on vegetation growth			• Analysis of landslide hazard and susceptibility maps • Prioritize for settlement on minor or low hazardous zones
2.	Rock, geology, lithology	Impacts on stability of slope as well as on vegetation growth	4	V	• Analysis of geology • Analysis of fault plains • Avoid constructing settlements or roads in instable slopes
3.	Seismic activity	Impacts on stability of slope	4	V	• Avoid constructing settlements or roads in instable slopes • Adopt early warning systems for earthquakes • Timely evacuation
4.	Extreme Rainfall	Wash away trees (vegetation) and unstable slopes or loose soil covers	5	V	• Analysis of annual precipitation and landslide hazard maps • Prioritize for settlement on minor or low hazardous zones • Implementation of bioengineering techniques prior to monsoon
5.	Deforestation	Affects both mechanical and	5	IV	• Public Awareness • Implementation of laws; rules and

		hydrological mechanism of vegetation and thus increases soil/slope instability			regulations • Awareness campaigns
6.	Forest fires	Destroy newly planted and old vegetation	3	III	• Public Awareness • Implementation of laws; rules and regulations
7.	Grazing of cattle	Destroy newly planted vegetation	2	II	• Public Awareness • Fencing • Establishment of community forests where people can graze their cattle
8.	Inappropriate agricultural practices	Affects hydrological mechanism of plant life processes	3	II	• Public Awareness • Implementation of appropriate agricultural practices
9.	Other improper / changes in land uses	Building settlements in unplanned way increases risks and vulnerability to landslides	3	I	• Public Awareness • Implementation of land use planning

From Table 6.3, it was evaluated that sometimes a low probability event may have enormous consequences or vice-versa. Factors with low probability should not be ignored. Close observation and evaluation are necessary. Accordingly, the prevention and mitigation measures should be planned on this basis, and priority should be given for reducing the triggers by possible ways.

6.3 What is 'severity' in case of landslides in Nepal?

Landslides have various consequences which vary at different degrees. The identified effects of particular triggering factors were rated for their severity. As discussed in Section 3.2, the severity refers to the extension of consequences measured with respect to something humans value. A severity level for effects of landslides was established considering one's perception and monetary value it worth. However, this opinion differs from different group of people, which can be observed in the survey (Refer Appendix) that was carried out among different groups of people. Nevertheless, this severity level rating is also enough to create landslide risk to human and environment of Nepal. Table 6.4 gives the severity rating for potential consequences of landslides in Nepal. A score of 0 to 5 had been given where 0 represented a very low (insignificant) severity, and 5 represented an extremely high severity.

Table 6.4: Severity rating for potential consequences of landslides in Nepal

Severity	Rating	Remarks
• People's deaths	5	
• People injured*	4	
• Property lost (houses, cattle, etc.)	4	
• Vehicle damaged	3	
• River blockage	4	
• Roads blocked/damaged	2	
• Water supply damaged	4	
• Drainage structure damaged	2	
• Agricultural lands destroyed	3	
• Electricity supply damaged	2	
• Communication breakdown	2	
• No significant impact	0	
Note: *Injuries of people is a subjective matter. It differs on the level of injury, from minor recoverable to permanent loss of body parts or to deaths in some cases. Hence, its severity rating differs accordingly.		

Priority for protection and risk prevention should be given by considering the severity level. It also adds surplus information in making useful decisions for risk assessment as well as hazard mitigation. However, severity varies on different perspectives.

During a geohazard, the value of lives are considered as the greatest asset, whether it is in Asia or Europe or any other continent, or even if it is a religion, Hinduism or Christianity or any. People feel blessed in surviving a geohazard. The reason is very simple that the value of lives is incomparable to any other consequences. However, there is a great necessity to oversee some other prospects of hazard impacts. To understand it more clearly, we take an example here. In Nepal, agriculture is regarded as the most important sectors of the source of food and local economy (ADPC, 2010). Livestock and agricultural lands are integral parts of the economy for most of the rural people in Nepal. Let us say a piece of farmland with (or without) crops or some livestock is lost during a landslide. On a surface level, it is observed that a piece of land and some livestock are lost. But the severity of those consequences lies inside the fact that the farmer has to face several impacts which are long-term. Reduction in the agricultural outputs, reduction in animal products and reduction of market value are some of the indirect consequences that arise with his losses. Such effects are something more than the loss of his house or other assets because for a farmer in the context of Nepal, his greatest assets are his agricultural lands and his livestock, which provide him his daily meal and a good life for his family. It takes comparatively a longer time to recover from these impacts because of his limited economic status. If we compare this scenario to a wealthy person who got his vehicle damaged in a landslide, it is not a high severity because he is easily able to buy another vehicle in some months. As the concern is about landslides and the people in Nepal, then the case of the farmer should be prioritized as his severity is far more than the rest. Here, the assistance of government and formulation of effective plans concerning the overall people (with similar economic status) of Nepal is paramount. Nepal, being a developing country, a majority of individuals lives in poverty. The consequences of a landslide that we just discussed in the context of Nepal (or consequence of any other geohazard) is something that most of the people has to bear all their life because of their long-term effects. Hence, this is also a major reason behind the poor economic status of the country as these kinds of hazard events push the poor people towards poverty and so to the country. It is advised to the concerned level for making effective plans that can address these kinds of severity issues.

The severity level can thus be justified as a result of an event that totally changes one's life (negatively). When the greatest asset for a human being is lost, then it is the highest severity of all the consequences of any unlikely event like geohazard. Therefore, landslide hazard mitigation plans should be made in such a way that they incorporate all these factors. These matters of severity are usually hidden in the shadows of other major issues. They pose a significant hindrance to the socio-economic development of the whole country. The severity of landslides in the context of Nepal varies on the basis of the social and economic status of people. Severity rating in Table 6.4 is a general approach and more subjective too. It is necessary to make remarkable research on the core impacts of a landslide rather than only depending on the moderate severities.

6.4 Probability-Consequence Diagram

As discussed in Section 4.3, a risk matrix similar to Table 4.1 can be drawn for analyzing the risks of landslides. The analyzed risk can be classified as acceptable or unacceptable on the basis of Table 4.2. High risks are considered as unacceptable risks, and medium and low risks are regarded as acceptable. Probability-consequence diagram as in Figure 6.4 was drawn on the basis of (Solheim et al., 2005), from the analysis that was carried out in above sections. A probability-consequence diagram is the one, where events are plotted concerning their probability of occurrence and their degree of consequences (as from the ranking we had made for both).

In the figure, the dotted lines at a level with score 3 is the one with occasional (50/50) likelihood and considerable (moderate) consequences which mean that the risk is at a tolerable level (ALARP region). The events having both the probability and implications very high possess high risk. For these events, various engineered and non-engineered techniques can be used to bring the unacceptable risks to an acceptable level. And a very strict attention should be given while formulating plans and strategies for prevention of landslides. However, carrying an unacceptable risk to an acceptable level is a difficult task but minimizing the possible consequences of landslides can be useful here.

Events which have low probability but high consequences can be brought to an acceptable level by implementing various impact reduction and mitigation measures. These actions include the formulation of strict government plans and policies, creating public awareness, planting trees and so on. Similarly, attention should be given to reducing the hazard and vulnerability for those events, which have high probability but lesser consequences. Activities like avoidance of settlement in hazard-prone areas should be done for this.

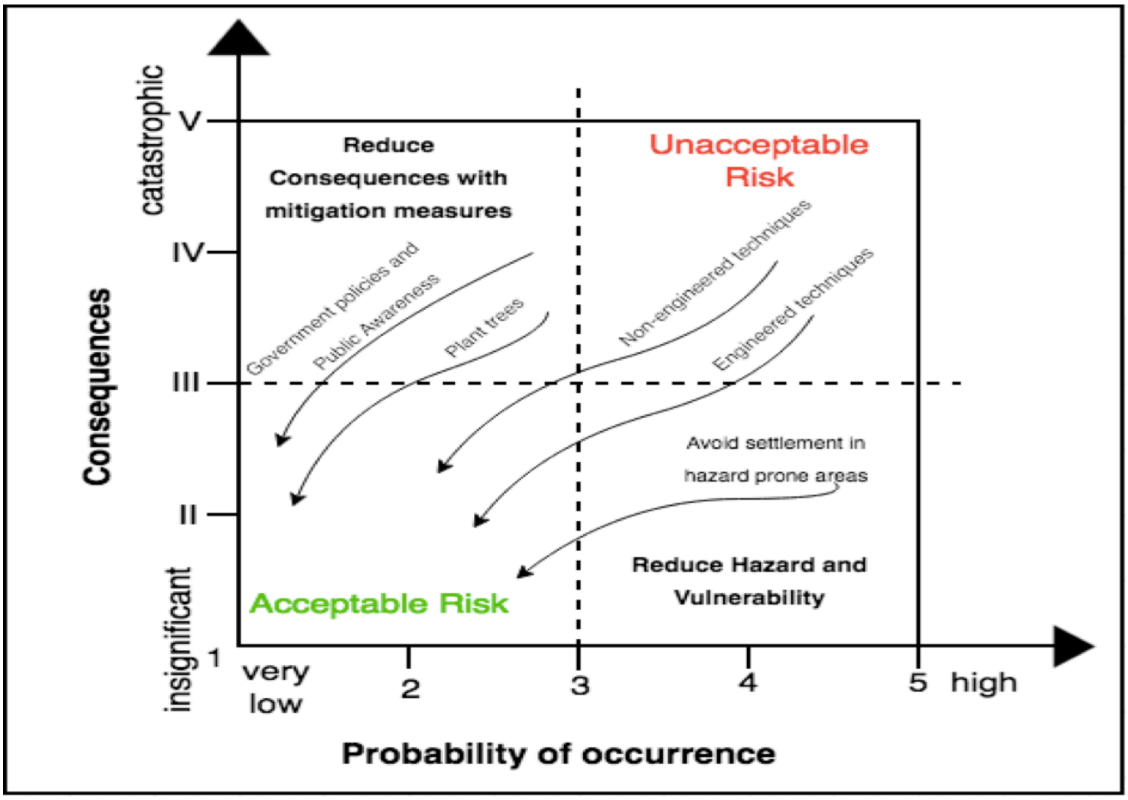

Figure 6.4: Probability-Consequence diagram for landslides (The direction of arrows in the figure points to bringing various level of risk to an acceptable level by implementing measures mentioned above the arrows)

6.5 Recommendation for Landslide Hazard Mitigation in Nepal

- Detail topographical survey should be done, and information regarding land features and conditions, ground water pressure, population density, socio-economic conditions and the pattern of housing as well as cultivation should be acknowledged before implementing any of the landslide mitigation measures. This information is also necessary before implementing any of the bioengineering techniques.

- Deforestation, as seen to be the primary cause of landslides in Nepal, public awareness is a very crucial factor for prevention and mitigation of landslides. Campaigns should be run at the local level regarding the impact of vegetation on slope stability and the root-soil interaction.

- Poor geological conditions are also observed to be the causes of landslides in Nepal. Hence, detailed geomorphological and geological assessments should be carried out before constructing any of the infrastructures like roads, water/ irrigation canals and hydropower reservoirs (dams).

- Landslide hazard risk assessment and landslide risk management plans should be developed at the very local level. The plans should be formulated by considering the regional difference.

- It is also essential to identify the areas most vulnerable to landslides with the connection to effects of Nepal Earthquake 2015.

- Areas vulnerable to potential landslides should be monitored and at very important sites, like sites near to larger population areas, early warning systems can be installed by identifying the possible tendencies for movements of soil mass, or rock.

- Land use patterns and agricultural practices should be improved. For this, integrated irrigation and cultivation practices can be enhanced. Also, appropriate planning for residential areas should be made.

- A proper survey of the site should be done before constructing any structures like roads, dams, canals, and appropriate design and engineering techniques can be followed.

- Most of the landslides in Nepal initiate floods by blocking the flow of rivers and streams. Landslide event in Mankha village is a good example here (discussed in Section 5.1 with Figure 5.3). Such secondary consequences of landslides should be addressed, and mitigation plans should be made accordingly.

- Precautionary measures should be followed not only before landslides but during landslides and even after the landslides too. The public should be made aware of these facts and appropriate actions can be enhanced for maintaining safety against landslide risks.

- Groundwater tables and pore water pressures should be investigated for the identification of highly saturated lands/slopes because saturated zones are prone to landslides.

- Soil bioengineering techniques should be improved with a proper understanding of its suitability and efficiency and should be carried out by considering the nature and type of the slope conditions and soil features.

- Direct losses of landslides include loss of lives, loss of properties and land, loss of infrastructures, and loss of livestock. But priority should also be given for mitigation of indirect losses of landslides like the decrease in production, degradation of drinking water quality and chances of water-borne diseases, the decline in the value of land, impact on people's feelings and emotions for losses of their valuable belongings, etc. Besides, the core severities of landslide impacts (the ones discussed in 6.3) should be addressed regarding the majority of people in Nepal.

7 Prevention and Mitigation Measures for Geohazards

The causes and consequences of most of the geohazards are often known. The extent of consequences depends on the nature, magnitude and frequency of hazards, mostly inhibiting the socio-economic development. There have been several measures implemented for prevention and mitigation of geohazards, but not every hazard is responsive to these measures. It is because of the nature of the hazards and the likelihood of their occurrence. Mitigation is about implementing activities for the reduction of adverse consequences of the hazards. It requires an in-depth knowledge of hazards and risks. Mitigation in our context of geohazards is all about reducing hazards and vulnerability and limiting the effects on people and environment.

Geohazards have huge impacts in the society and to the whole nation. They become the main causes of the hindrance for the development of a country. Some of the geohazards can be predicted for which a well understanding of this geo-hazardous phenomenon is required. Prediction of the occurrence and its behaviors needs a detailed study and understanding of the geological processes, conditions and structure of any particular area. Thus, various measures can be implemented timely for the reduction of the possible impacts of geohazards and prevention of huge loss or damages to the environment. (Jaedicke et al., 2008) mentions that an improved understanding of the relationships between meteorological conditions and geomorphologic processes leading to geohazards is crucial for a better planning of mitigation measures. Combining both preventive as well as mitigative measures can reduce risks of geohazards. It can be achieved by identifying hazardous areas by a proper understanding of the patterns of behavior of geological processes and phenomena that pose hazards.

Most of the geohazards pose similar threats to human and the environment. Hence, the prevention and mitigation measures for the risks associated with them are mostly similar. (ICG, 2010; Lacasse et al., 2012; Nadim, 2009) classifies mitigation measures for the risks associated with geohazards into six categories namely:

1. Land use plans
2. Enforcement of building codes and good construction practice
3. Early warning systems
4. Community preparedness and awareness building
5. Construction of physical protection barriers
6. Network of escape routes and 'safe' places

A mitigation strategy for the risks associated with geohazards is established by combining above-mentioned measures of mitigation. This includes various steps (ICG, 2010; Kalsnes et al., 2010; Lacasse et al., 2012), which are:

1. Identification of potential disaster triggering scenarios and the associated hazard level
2. Analysis of possible consequences for the different scenarios
3. Assessment of possible measures to reduce and/ or eliminate the potential consequences of danger

4. Recommendation of specific remedial measures and relevant reconstruction and rehabilitation plans
5. Transfer of knowledge and communication with the authorities and society

No matter this strategy should be adopted all over the world, it focuses on establishing and promoting proper land-use planning and construction practices, basically in developing countries as they are more vulnerable to the risks of geohazards. It helps to synchronize the human activities that increase risks of geohazards and hence prevent the settlement of people and societies in high-risk areas. Mitigation strategy needs a lot of effort and research.

Geohazards are complex phenomena and usually one hazard can be responsible for the generation of other hazards. Earthquakes are one of those examples, whose occurrence consequently triggers landslides or tsunamis. Apart from this, modification of the existing environment largely increases the frequency and severity of geohazards and also the threats to human occupancy. Risk mitigation and reduction measures can change with the pace of time. Measures been used several years back may not be appropriate in the present. The density of population, people's status, nature of the changing environment and the knowledge and experience one has gained from the past incidents make a huge difference here. It is always seen that the awareness regarding the occurrence and consequences of geohazards among the people and the implementation of various risk reduction, prevention and mitigation measures are often more emphasized immediately during the periods of hazards. But the concern of people, society or even the whole nation declines consequently with the passage of time. This is a serious issue, which needs to be overlooked upon; thus ensuring for the prevention and mitigation of hazards in the future.

Geohazards are such events, which may occur either as an isolated event or sometimes in a combined form of several geohazards. They can be triggered by natural causes of by anthropogenic causes. Geohazards pose threat to humans, assets and existing environment. Public awareness is the foremost important measures of risk mitigation of geohazards. It is the people, who are responsible for triggering geohazards, who are the vulnerable groups to impacts of hazards and it is also them who are responsible for creating a safer environment with implementation of mitigation measures in the nearest future. We can say that people are the crucial organs in every aspect of geohazards. Making oneself aware of the possible hazards is difficult task but not impossible. It takes time to make people aware of the facts about geohazards. Hence, public awareness is one of the foremost important factors of risk mitigation. Until and unless there is a realization that population is at risk, creating public awareness is almost impossible.

A detailed study of geologic and geomorphic properties of land or the earth is required for assessing the risks of geohazards. Several techniques have been developed so far in recent years for this purpose. Satellite remote sensing data and GIS are used as outstanding means for effective and efficient techniques in monitoring and mapping of geohazardous areas. Similarly, Early warnings for risks of geohazards should be able to give a prior notice to the people and be prepared for safety. (Lacasse et al., 2012) mention that an early earning system can be an effective risk mitigation measure that gives enough time to move the elements at risk out of harm's way. They are an implementation of technological solutions. They also include other important parts like human factors, social elements, communication and decision making authorities, the form, content and perception of warnings issued, population response, emergency plans and their implementation and plans for reconstruction or recovery. Early warning systems should be implemented in areas with high risks. (Michoud et al., 2013) has discussed on this implementation in more detail by taking one of the geohazards (landslides).

7.1 Need of Broader Thinking for Prevention

Geohazards are those events, whose probability of occurrence is low in comparison to their consequences. Mitigation, prevention, preparedness and response strategies must be planned beforehand hazard incidents. Apart from making a proper decision for a geohazard scenario, implemented risk management approach should be such that, it causes an appropriate allocation of resources and achievement of mitigation strategies. Since geohazards possess a very broad and interdisciplinary concept, they should be addressed both at local and global levels. There is a need for long-term prevention and planning. New methods and plans must be made for proper urban development planning and construction of anti-seismic buildings so as to minimize the vulnerabilities of geohazards. The risk of geohazards is increasing with growing population and changing global climate. Due to this reason also there is a need to think broader and enhance a risk approach that can reduce such risks.

When a geohazard occurs, several measures are addressed to fulfill the immediate needs of people. Such measures are usually short-term. Risk mitigation measures are effective only when they are focused on meeting long-term goals of decreasing vulnerability and associated consequences. It also requires commitment of the whole society and the nation for a better acknowledgment of obstructions (for mitigation practices) and finding out advanced solutions. There is a need to shift our focus from recovery-response towards prevention-mitigation, building resilience and reducing risks, learning from experience and avoiding past mistakes (Lacasse et al., 2012).

We know that hazards are mapped regarding their likelihood of occurrence, their impacts to livelihood and the environment, and other spatial and temporal characteristics. When these factors are analyzed, then usually there is a belief that the risk assessment process is complete. It is a misconception because assessing risks of geohazards are complete with an analysis of hazard and vulnerability. It is also important to find out the people at risk or the vulnerable group for any particular hazards. The ultimate goal of risk management should be such that it provides safety to the people and prevent losses due to geohazards. Henceforth, it must be focused towards achieving a sustainable and systematic development by managing risks of all types of geohazards with a high concentration on hazard and vulnerability. It helps in effective and efficient utilization of both financial and personnel resources.

In the recent years, mitigation and prevention of risks posed by geohazards have been an issue of keen interest. But according to (Kalsnes et al., 2010; Lacasse et al., 2012), there is a need of proactive approach to risk management considerably to reduce loss of lives and material damages. This method is all about analyzing a hazardous situation to determine the significant risks and taking further steps to minimize its probable impacts. It also helps in decreasing the likelihood of various effects of geohazards that may happen in the nearest future and in reducing the possible consequences. However, in a long run, there is a need to rethink about coping and mitigating strategies for geohazards because of the changing probability of factors like the number of population, pattern of settlement, climatic conditions and so on. As future is uncertain, we never know that geohazards may occur within a shorter or longer period. Consequently, measures designed for a given period (say 1 in 100 years' time) would no more be accountable. Thus, new adaptive measures should be formulated.

8 Conclusions and Recommendations

- The risk of geohazards is a combination of a hazard, vulnerability and exposure. However, complexity in human civilization (increase in urbanization, random constructions, etc.) and global climatic change increase the sources, probability of occurrence and severity of geohazard risk.

- Increasing trends of precipitation and wind speed, extreme weather events and regional climatic variation are the leading causes of increasing frequency and risks of future geohazards like snow avalanches and rockslides in Norway. Hence, there is a need for scientific research on changing hazardous conditions by evaluating the past hazards, their occurring patterns and potential triggers.

- Geohazards are low probability and high consequence events which initiate other secondary hazards. Henceforth, one should also be aware of this fact and besides implementing measures and strategies for risk mitigation, it is also crucial to take careful steps for response and recovery after a geohazard occurs. Focus should also be given to reduce further loss of lives and properties.

- Landslides are significant geohazards in Nepal. The efficiency of soil bioengineering techniques that have been adopted for centuries for landslide hazard prevention can be increased with a proper understanding of root-soil interaction and the role of vegetation in improving slope stability. Awareness and strict laws against deforestation are also essential.

- Seeking for achieving a zero risk from geohazards is utterly impracticable. It is also beyond one's hand to make investments for making the lives 100 percent safe. Thus, besides making approaches for feasible risk mitigation and risk management, there is a need for creating a balance between understanding geohazards, risk acceptability, preparedness and risk management strategies.

- Risks cannot be eradicated, but they can be managed. However, with the advancement of technology and knowledge, changes should be brought in risk management techniques. As a risk analyst, geohazard consequences must also be analyzed to bring the risk at acceptable level and be aware of the fact that the nature of geohazard affects the method of risk acceptance. Therefore, further risk reducing measures should be planned accordingly. But, in today's day, there is a need of responsibly accepting proprietorship of risk assessment and control processes by every individuals for achieving success in risk management approaches and making them an efficient one.

- In a long run, there is a need to rethink about coping and mitigating strategies for geohazards because of the changing probability of factors like the number of population, the pattern of settlement, climatic conditions, etc. One cannot precisely predict about geohazards. Subsequently, measures designed for a particular period would no more be accountable then.

Thus, it is required to think broadly for new adaptive and preventive measures for a better future.

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Appendix