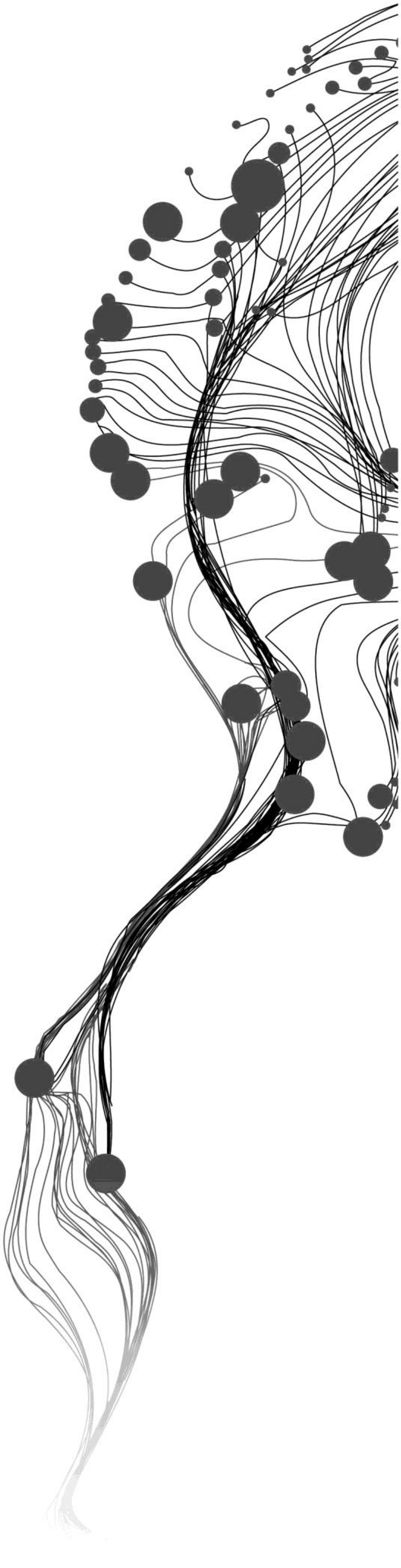
EVALUATING PROTECTIVE FUNCTION OF FOREST AGAINST ROCK FALL HAZARD: A CASE STUDY OF HIMALAYAN TEMPERATE FOREST UTTARKASHI, INDIA

ANKIT RAWAT
March, 2012

SUPERVISORS:

Dr, C.J, (Cees) Van Westen
Dr, I.C, Das
Dr, K.K, Das



EVALUATING PROTECTIVE FUNCTION OF FOREST AGIANST ROCKFALL HAZARD: A CASE STUDY OF HIMALAYAN TEMPERATE FOREST UTTARKASHI, INDIA

ANKIT RAWAT

March, 2012

Thesis submitted to the Faculty of Geo-Information Science and Earth Observation of the University of Twente in partial fulfilment of the requirements for the degree of Master of Science in Geo-information Science and Earth Observation.

Specialization: Natural Hazard and Disaster Risk Management

SUPERVISORS:
Dr. C .J. (Cess) Van Westen
Dr. Iswar Chandra Das
Dr. Kunal Kumar Das

THESIS ASSESSMENT BOARD:
Prof. Dr. A. (Alfred) Stein (Chair)
Prof. Dr. V.G (Victor) Jetten
Dr. C .J. (Cess) Van Westen (Supervisor)
Dr. P.K. Champati Ray (Observer)
Dr. (Nicholas) Hamm (Observer)

ABSTRACT

Rock-fall is a common slope failure process in steep mountainous landscape, characterized by rapid downwards slope movement of one or more boulders through free fall, bouncing or rolling. Many mountain forests effectively protect people and assets against natural hazards. This natural slope failure process becomes more concerning with the presence of high vulnerable elements down the slope like roads, transport, buildings, peoples and agriculture land. Their protective effect is, however, not constant but depends on forest dynamics.

The main objective of this study is to analyze the role of protective forest against rockfall impact along a road in a Himalayan setting, by means of a dynamic GIS-based modelling approach. This thesis shows that simulation models such as 'RockyFor 3D' for investigating the protective function of the forest and for optimizing its management. In present study the rock fall hazard is assessed along the road corridor (NH-108) between Uttarkashi to Gagnani, including roadside residential areas and other infrastructures. The region is continuously under impact of natural hazards occurring due to slope failure, causing societal and economic losses.

The efficiency of protection forest, against rock fall hazard depends on the forest stand parameters such as tree density, tree diameter, species composition and spatial arrangement of trees in forest. These parameters directly regulate the energy dissipation potential of trees on collision with a rock mass. The different remote sensing and GIS derived inputs used for present study. The satellite data and other ancillary information are used for two main purposes for field work and preparing for inputs for rockfall modeling. During pre-field work the identification potential rockfall source area were carried out along the National highway 108, using DEM-based morphometric analysis, in order to select proper rockfall site with presence of forest cover as most of the rockfall events on national high 108 are resulted from human activities like road construction, mining , blasting etc without presence of forest cover..The various instrument used during field work are GPS, Haga-Altimeter for measuring tree-height, Laser-distance meter use to locate the distance between trees in a forest stand, metallic tape for diameter measurement etc.

The protective effect of forest stand was assessed by quantifying the change in the impact rockfall trajectories between the scenarios of current forest cover and non forest cover for different rockfall site with varying dimensions of boulders. The model simulation shows that lithology in general does not affect the protective function of forest of in great deal. The reliability and quality of input data for proper rockfall modelling were assessed on the basis of observed and simulated rockfall pattern, with spatial distribution of rockfall trajectories, run-out distance and the mean impact height of boulder on the trees. The outcomes of the study showed that the forest stands are effective in mitigating the impact of rockfall hazard. Furthermore, the model also simulated the optimum forest stand density of the protection forest to offer maximum resistance against rockfall hazard. The model also simulated the tree impact height of falling boulders which matches closely with the tree impact height as observed in field condition. This proved the repeatability and transferability of the model in Himalayan settings.

Keywords: Rockfall modelling, Protection forest, Rockyfor3D, Uttarkashi, GIS, DEM.

ACKNOWLEDGEMENTS

Bringing this thesis to a successful end is a great achievement for me. I thank everybody for their support, help and encouragement in accomplishing this task. I would like to send my gratitude and regards to:

- Dr. C.J. (Cees) Van Westen, ITC Supervisor, for guiding me throughout my research phase, his scientific and critical comments was instrumental in designing a good research.
- Dr. Luuk K. A. Dorren, EcorisQ, for providing the Rockyfor3D model and relevant comments on the implementation of the model during the project phase.
- Dr. I. C. Das and Dr. K. K. Das, IIRS Supervisors, for their timely comments and steering me out from difficulties.
- I sincerely thank Ms. Vandita Srivastav for helping me through the tough times of my thesis
- I express my gratitude to Dr. S.P. S. Kushwaha, Dr. Sarnam Singh, for the valuable suggestions and support in my field work.
- Dr. P.K. Champati ray for his valuable comments and suggestion for improving the thesis.
- Dr. M.C. J. (Michiel) Damen for imparting his skills knowledge and for this excellent.
- Pradeep Kumar, JRF for all the support, strength and motivation all through my thesis and my stay in IIRS
- All my friends in IIRS for supporting me in successful completion of my thesis especially the most awesome people Abhijeet Kumar Parmar, Chittaranjan Singh and Teja Malladi
- I specially thank Mr. Deepak Upadhyay, for all the midnight tea conversation and those fun times.
- IIRS Computer Maintenance Cell for their excellent system and software support.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

1.1. Rockfall Hazard

Rock-fall is a common slope failure process in steep mountainous landscape, characterized by rapid downwards slope movement of one or more boulders through free fall, bouncing or rolling (Varnes 1978). This natural slope failure process becomes more concerning with the presence of high vulnerable elements down the slope like roads, transport, buildings, peoples and agriculture land. In the context of the Himalayan Mountainous System (HMS), rock fall process is more prominent and hazardous due to the availability of greatest relief, high potential energy, high seismicity, high weathering potential and large extent of fractured rock surfaces (Shroder and Bishop 1998). In addition to this, vulnerability to natural hazards in the Himalayan region has increased manifold with time due to considerable increase in population and unplanned urban expansion(Rautela 2005). According to the Census of India (2011) Uttarkashi, which falls under Central Himalayan range alone, has witnessed a population growth from 2.9 million to 3.3 million, with rise in population density from 37 to 41 persons per km^2 in a decade.

In present study the rock fall hazard is assessed along the road corridor (NH-108) between Uttarkashi to Gagnani, including roadside residential areas and other infrastructures. The region is continuously under impact of natural hazards occurring due to slope failure, causing societal and economic losses. The severity of risk over the road stretch was estimated by the frequency of hazardous events recorded, over a relatively short interval of time. The hazardous event occurrence and associated loss and problems are tabulated –

Table 1-1 Summary of landslide and rockfall events that occurred along the (NH-108)
Source: Newspapers (Amar Ujala & Hindustan Times)

Hazard event	**Date & Location**	**Loss/problem reported**
Rockslide	27 June 2011 Dharasu,Chliyasan	1 child die, NH-108 block for 18 hrs, Gangotri pilgrim struck due to road blockage
Rockfall	28 June 2011 Nalupani	3 cars damaged and pushed in the Bhagirathi river. And 550 vehicles struck due the event in blockage.
Rockslide	9 July 2011 Thrang	NH-108 closed for 8 hrs and 200 pilgrims struck in rockslide.
Landslide	16 July 2011 Thrang	200 vehicle struck due to landslide
Rockfall	22 July 2011 Vasuti taal	8 Mountaineer's died
Landslide	7 August 2011 Maneri	Damage of electricity line and water supply in the area
Landslide	8 August 2011 Naitala	Five houses damage and seven houses were excavated.
Rockslide and Landslide	12 August 2011 Sainj	Road block for five days, resulted in food scarcity condition

.

1.2. Problem statement (Research Gaps)

Frequent occurrences of rockfall events have made the Himalayan region highly vulnerable. There are many rockfall sites in the region which are producing disastrous impact on down slope areas (Joshi and Pant 1990; Gupta 2004; Deka and Pachauri 2006). The potential impact of rockfall hazard in study area is further aggravated by the presence of one of the most frequented road corridors (NH-108) which leads to prominent pilgrimage sites like Gangotri and Yamunotri and further connects the international border with China. Moreover the government effort and policies for rockfall protection are proved ineffective due to inaccessibility of terrain, lack of economic resources and large spatial coverage of hazardous sites. Thus, the presence of forest stands is the only feasible and effective protective measures to mitigate the impact of rockfall hazards in Himalayan region. These forest stands protect the down slope settlements and roads by obstructing the movement of rocks mass (Figure 1-1). This calls for a detailed investigation of the nature and parameter of protection forest stand to be established in order to mitigate the impact of rockfall hazard events effectively. Knowledge on optimum stand parameter's such as stand density, spacing between trees, Diameter at Breast Height (DBH), Mean Tree Free Distance (MTFD) and tree species composition are handful in evaluation and management of protection forest. Further there have been no studies accounting for the role of protection forest against rockfall hazard in the study area and the Himalayan region in total resulting in lack of awareness about the importance of forest as a protection factor against rockfall. Hence this study has been taken up to address the aforementioned issues.

1.3. Research objective

The main objective of this study is to analyze the role of protective forest against rockfall impact along a road in a Himalayan setting, by means of a dynamic GIS-based modelling approach and to achieve this general objective, the specific objectives of research is as follows-:

- To identify and map the distribution of potential rockfall source areas.
- To access the potential impact of rockfall under forested and non-forested scenarios.
- To analyze the optimal stand density for rockfall protection and role of lithology on protective function of forest.
- To, analyze whether the data requirements in an Indian context are sufficient for proper rockfall modelling.

1.4. Research questions

The main research questions related to research objectives are as follows-

- How potential rockfall source areas are identified, particularly on forested area?
- How protective effect of forest stands can be assessed against down slope vulnerable features?
- How lithology in the study area affects protective function of forest against rockfall?
- What should be the optimum stand density of protection forest for minimizing the impact of rockfall hazard?
- Are the condition and data requirement are sufficient for the proper rockfall modelling using RockyFor3D model in the study area?

2. LITERATURE REVIEW

2.1. Protection forest and Rock fall

Protection forest is a forest with a primary objective to provide protection, to people and their properties against the impact of natural hazards and adverse climatic condition (Brang 2001) . In Mountainous region the damage potential of natural hazards like rock fall and snow avalanches can effectively be reduced or mitigated by the presence of protection forest on hill slopes (Motta and Haudemand 2000; Corominas et al. 2005).The Indian National Forest Policy Act 1988 also concluded that "In the hills and in mountainous regions two-third area must be under forest or tree cover to ensure the stability of fragile eco-system against hazardous processes". The forests, on rockfall prone hill slope provide direct protection to assets down the slope against the impact of falling rocks and boulders, resulting in safer environment for inhabitants. Moreover, protection forest is a cheaper and ecologically friendly means of mitigation measure against rock fall hazard as compared to engineering measures and also the latter, deteriorate with time and have limited spatial extent (L. Dorren et al. 2005).

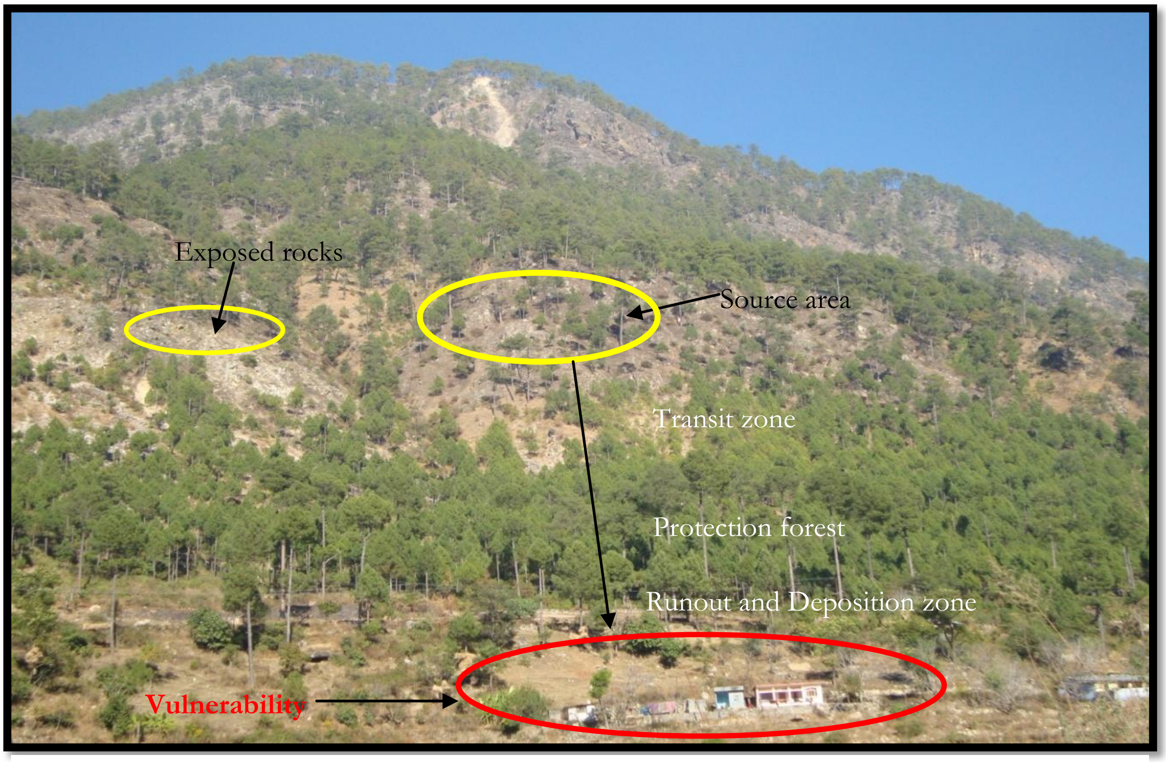


Figure 2-1: Dynamic phase on active (forested) rockfall slope. (Hinna, Uttarkashi)

The efficiency of protection forest, against rock fall hazard depends on the forest stand parameters such as tree density, tree diameter, species composition and spatial arrangement of trees in forest. These parameter directly regulate the energy dissipation potential of trees on collision with a rock mass (Hoesle, 2001) and also the probability of collision. Therefore in rock fall prone sites, forest with dense stand structure and small gaps between trees, in parallel direction to the slope ensure the high level protection (Omura & Maruma 1988). Managing forest for their protective effect against rock fall hazards is completely different from the timber production point of view. Managed protection forest ensures the long term protective effect against hazards with practice of silviculture system such as shelter wood, selection or coppice systems that aims more number of trees by natural regeneration trees on protected site (Schonenberger and Brang 2004). The rockfall and protection forest research studies in European Alps provide management guidelines and minimum standard values for stand parameters to ensure effective rock fall protection (Frehner *et al* 2005).

Table 2-1: Management guidelines for rock fall protection forest (Frehner *et.al*, 2005)

Zone	Contribution of forest	Minimum standard	Ideal standard
Release/Source area	**Moderate**	**Backbone trees** (Strong anchoring and Stable tree)	
Transit zone	**High** Rock up to 0.05 m^3 (diameter about 40 cm)	**Horizontal structure** ≥ 400 trees/ha with DBH >12 cm	**Horizontal structure** ≥ 600 trees/ha with DBH >12 cm
		Favourable if, coppicing nature.	
	Rocks 0.05 to 0.20 m3 (diameter 40-60 cm)	**Horizontal structure** ≥ 300 trees/ha with DBH >24 cm	**Horizontal structure** ≥400 trees/ha with DBH >24 cm
	Rocks 0.20 to 5.00 m3 (diameter 60-180 cm)	**Horizontal structure** ≥150 trees/ha with DBH >36 cm	**Horizontal structure** ≥200 trees/ha with DBH >36 cm
	Additionally for all rock sizes	Stem distance <20m (in direction to slope surface) Lying logs and stumps can, complement to standing trees.	
Runout and deposition Zones	**High** The effective minimum diameter of trees is considerably smaller than in the transit zone. Lying logs on slope surface are recommended.	**Horizontal structure** ≥400 trees/ha with DBH >12 cm	**Horizontal structure** ≥600 trees/ha with DBH >12 cm
		Horizontal structure Stem distance <20 m (in direction to slope surface) Favourable if, coppicing nature	

2.2. Rockfall Modeling

Rock fall is a highly complex process as the movement of boulders detached from rock fall source to deposition zone is quite unpredictable (Erismann and Abele 2001; L. K.A Dorren 2003) . This results in the uncertainty of quantification and mapping vulnerability against the rockfall hazard event. To overcome this uncertainty issues associated with rockfall events, the GIS-based rockfall models are used that assess the spatial extent of rockfall–run out trajectories and efficiency of rockfall protection measure available on site, Knowledge obtained from model simulations can be help in rock fall risk reduction planning. In the Himalayan region rockfall modelling can be important tool, in monitoring and mapping of rock fall susceptibility due to presence the large inaccessible rock fall areas and particularly, in evaluation the protective effect of forests, as these are the only means of protection measure against rockfall hazards in the region.

In a recent review on rockfall modelling approaches Dorren (2003) categorized rockfall models in three main groups' namely empirical models, process models and GIS-based models.

2.2.1. Empirical models

Empirical rockfall model calculate the rockfall mechanics, based on the empirical observation made for particular slope site. They are generally based on empirical relationship between topographic factors and length of the run out zones of rockfall trajectories (Dorren 2003). Tianchi (1983) develop empirical relation between volume and distance travel by rock material under rockfall event. Similarly Heim (1932), suggest *Fahrböschung* angle concept to predict the rockfall run out zone. It is the angle between a horizontal plane and line from the top of a rockfall source area to the stopping point of rockfall trajectory. In 1993 Evans and Hungr suggested a concept of minimum shadow angle, the angle form by line connecting the highest point on talus slope and stopping point of longest run out boulder. Based on studies of run out distance prediction, it was found that the minimum shadow angle lies in the range between 22° to 30° (Hungr and Evans, 1988). Latter in 1999 Evans and Hungr, found the minimum shadow angle value 27.5° based on experiment carried, on sixteen talus slope in British Columbia.

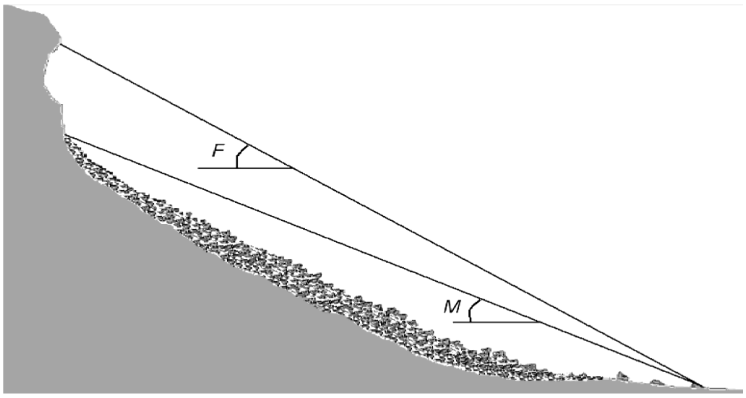


Figure 2-2: *Fahrböschung* (*F*) and the *minimum shadow angle* (*M*) of a talus slope. (Modified from Meissl, 1998)

2.2.2. Process based models

Process based rockfall model simulates the rock fall process through various types of motion of falling rocks depending on the slope of the surface. Ritchie (1963) define the type of motion, falling rocks follow based on the slope gradient depicted in Figure 2-3 below.

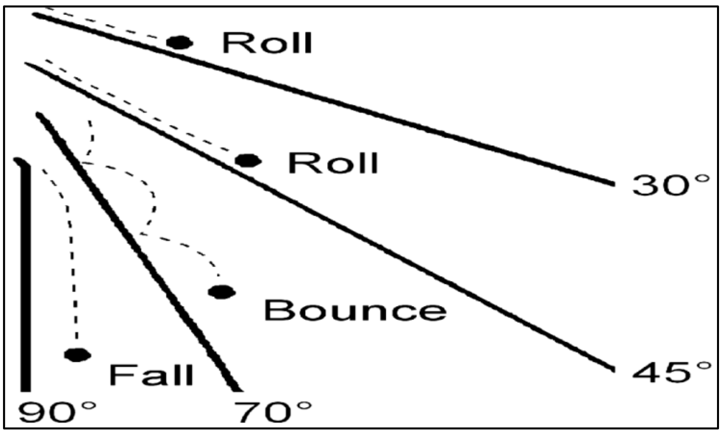


Figure 2-3: Type of motion during down slope movement, related to slope gradient (Source- Ritchie, 1963)

(Kirby and Statham 1975) developed a process-based rock fall model which first calculates the velocity of falling rocks at the base of cliff. On the basis of fall velocity of boulders, the parallel and tangential velocity components to slope surface were calculated, assuming that the fall velocity is conserved during the first impact on the slope. At last the stopping position of boulders was calculated by the ratio of fall velocity and frictional force due surface roughness. In addition to (Kirby and Statham 1975), many other researchers developed similar types of process based rockfall models. Most of these rockfall models are two-dimensional slope -scale models and rock fall track are defined by the mean slope gradient.
In the past decade three-dimensional rock fall models are also developed to investigate rockfall process at slope scale. The rockfall model required a high resolution Digital Elevation Model (DEM), friction coefficients and coefficients of normal for accurate prediction of rockfall track as these affects velocity and energy and bounce height of moving boulder (Descoudres and Zimmermann, 1987).

2.2.3. GIS based models

GIS based rockfall models are the most recently developed groups of rockfall models, which use raster based input for GIS analysis (L. K.A Dorren 2003). GIS-based rockfall models works on the basis of three main procedures, first identification of rockfall source areas, followed by determining the fall track direction and finally calculating the run out distances of falling boulders (Hegg and Kienholz, 1995). Meissl (1998) developed two GIS-based rockfall models, the first was *Schattenwinkel (shadow angle)* based on the minimum shadow angle principle and the second model was *Geometrische Gefälle* based on the angle of shortest line between the top of the rockfall source area and the stopping location. But latter Meissl reported none of the two rockfall models was able to perform at regional scale due to inability in handling of large GIS datasets. Before this in 1990 Van Dijke and van Westen developed a GIS-based rockfall model for regional scale rockfall hazard assessment, in this model the fall track direction is calculated on the basis neighbourhood analysis of Digital Elevation Model (DEM) values. With the integration of three-dimensional GIS analysis to the available empirical and process rock fall modelling approach, fall track prediction has become more accurate also over regional scales. Further the 3D approach in rockfall modelling provides more realistic evaluation of the rockfall process, as it accounts the bounce height and tree-boulder impact height of boulder during the movement which is decisive in accurate fall track prediction.
For the present study on evaluating the protective function of forest against rockfall, a GIS-based Rockyfor3D is used, described in the chapter 4.

3. STUDY AREA

The study area is located between 30^0 47' 29''N to 30^0 54' 45''N latitude and 78^0 37' 41''E to 78^0 44' 03''E longitude, in the Uttarkashi district of Garhwal Himalayan region Uttarakhand state, India. Three rockfall sites was selected along of National Highway -108, the highway extends from Uttarkashi to Gagnani via Naitala, Hinna, Aungi, Maneri, Sainj and Bhatwari these places are frequently affected by slope failures causing significant loss of life and property. The importance of this road stretch further increases as it leads to Gangotri and Gaumukh, which are considered as holy places in Hindu Mythology, resulting in death of several pilgrims and visitors every year, particularly during the festive months. Further, it also connects four main hydroelectric projects at Bhagirathi valley namely Bhaironghati, Loharinag-Pala, Pala-Maneri and Maneri-Bali Stage-I. Moreover, the study area has been selected because some studies have been conducted by (Iswar Chandra Das 2011) on mass movement; hence a lot of ancillary data was already available for the research.
The study area is concentrated on three rockfall sites at Gagnani, Aungi and Hinna to assess the protective function of forest against the rockfall hazards. The study was limited over three rockfall sites; because there is no prior information on forest stand parameters are available for the study area. Therefore field sampling was carried out at these sites.

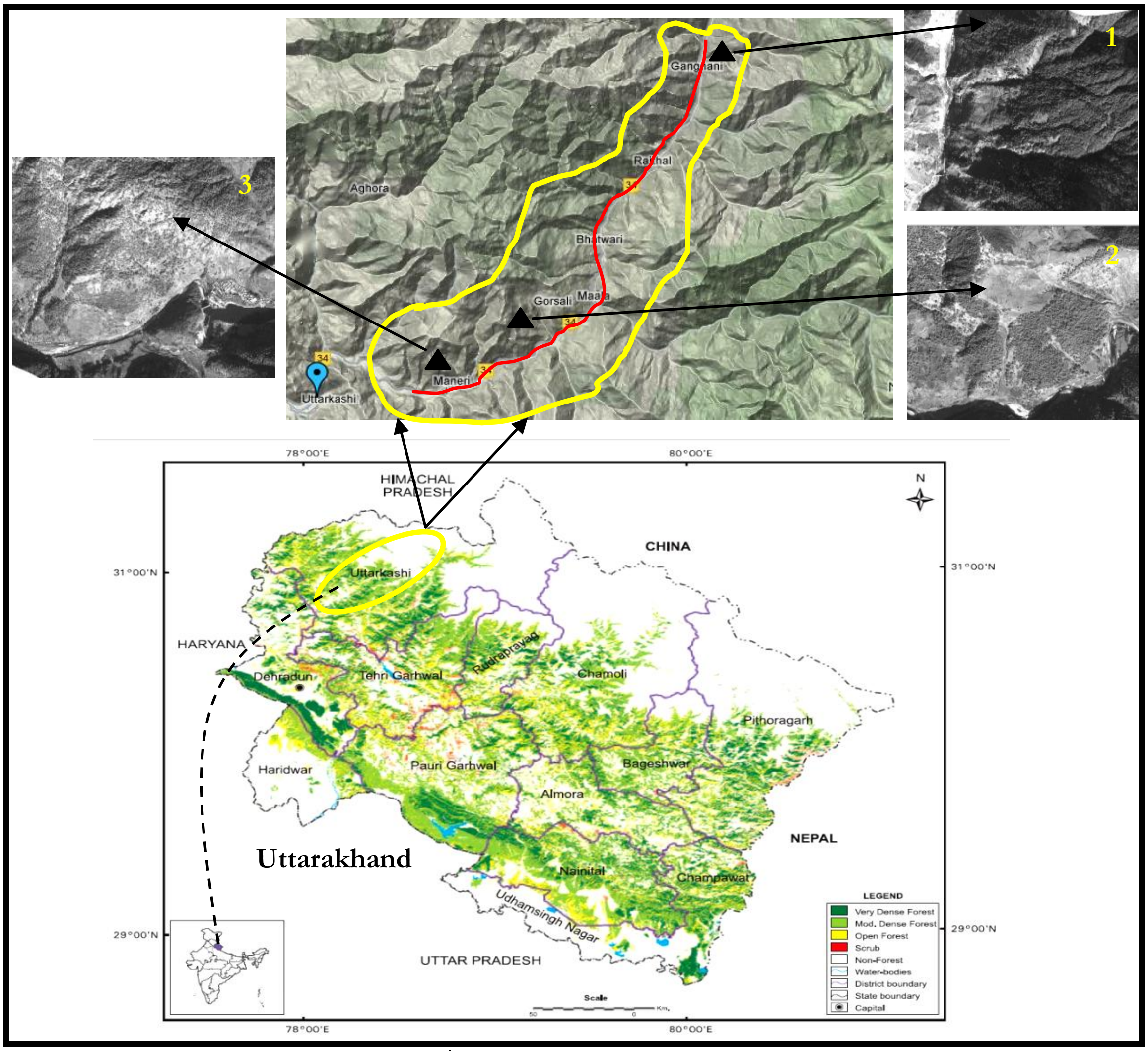


Figure 3-1: Location of study sites (▲) Gagnani (1), Aungi (2) and Hinna (3) along NH-108.

3.1. Rockfall sites

Rockyfor model was applied to three mountain forest sites along the NH-108 in Uttarkashi area, above Fig.3.1, gives the overview of three sites selected. The first site (Gagnani) was suitated (Latitude-30.90, Longitude-78.68) around 40 kilometers from Uttarkashi at elevation range of 1952-2445 meter from Mean Sea Level (MSL), with a mean slope of 48°. The site consists of Calc-Silicate Gneiss rock type under Higher Himalayan Crystallines formation (Purohit *et.al* 1990). The forest at the site is dominated by *Pinus roxburghii* tree species more than 98%, with mean diameter of 125 cm and mean height of 25 m, with total forested length from rock fall source to foot of the slope 200 m. The rockfall source area is located about 5 m above the slope surface, the dominant rock deminsion found in the transit zone were 0.30 m to 0.50 m.

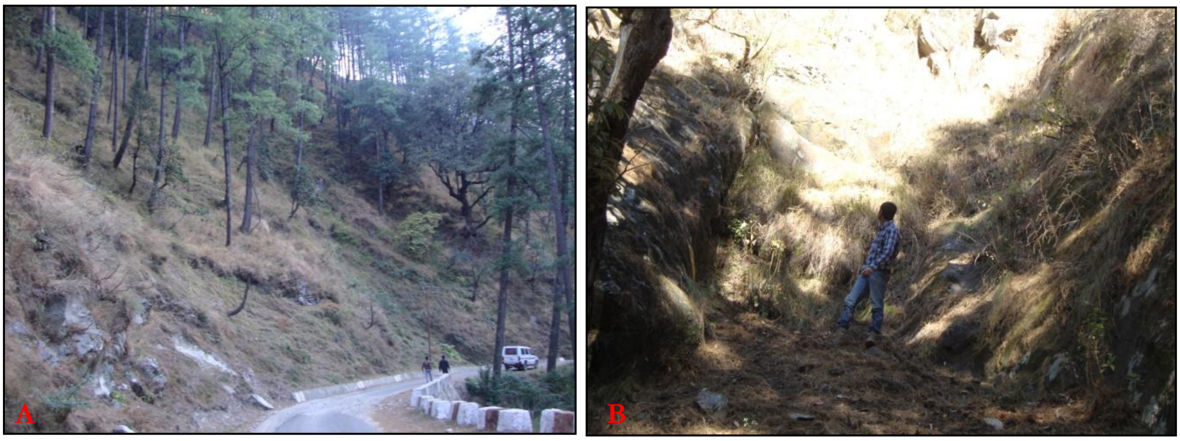


Figure 3-2: (A) Pine forest stand and (B) Rockfall Source area (at Gagnani).

The second rockfall site is suiated (Latitute-30.75, Longitude-78.57) around 20 Kms from uttarkashi at Aungi, this rockfall site is a ancient rockfall site characterized by huge boulder deposits on the slope surface. The site lies at the talus of 1950 m high mountain cliff, with mean slope of 42° with a elevation range of 1300-1500 m, the area composed of Quartzite rock type of lesser Himalaya crystalline a low grade metamorphic rock.. The forest stand is dominated by broad leaved tree species *Toona ciliata* with low stand density 105 stems/hectare, with mean DBH of 258 cm, the forest stand shows higher density toward the foot of slope compare to upper part of talus where scattered trees are present.

Figure 3-3: (A) A rock stopped by tree and (B) Measurement of fallen block dimension (at Aungi)

The third site is Hinna situated (Latitude-30.74, Longitude-78.51) 15 km from Uttarkashi, the forest stand at Hinna is dominated by *Pinus roxburghii* with high stand density of 828 stems per hectare and mean diameter of 68 cm with forested slope length of 105 m. The rock type at Hinna site is quartzite, with dominant boulder size of 0.80 m to 1.20 m. The forest stand at Aungi provides protection to down slope settlement and NH-108. The detail characteristic of rockfall sites are presented in Table.3.1.

Figure 3-4: (A) Pine forest stand and (B) Boulder block by tree (at Hinna)

Table 3-1 : Characteristic of three rockfall sites.

Rockfall site	Elevation (m)	Mean slope (°)	Forest Characteristic	Soil type	Dominant rock size(m)	Vulnerability
Gagnani	1952-2445	48	Stand density- 215stems/hec Mean DBH- 125cm Dominant tree species- *Pinus roxburghii* Forested slope length- 200 meters	Coarse loamy soil with sandy surface, moderately shallow	0.30-0.50	Road(NH-108)
Aungi	1350-1500	45	Stand density-105stems/hec Mean DBH- 258cm Dominant tree species- *Toona ciliata* Forested slope length- 80 meters	Loamy soil with excessively drained and deep	1-2	Road(NH-108) Settlements area
Hinna	1250-1450	42	Stand density- 828 stems/hec Mean DBH- 68 cm Dominant tree species- *Pinus roxburghii* Forested slope length- 105 meters	Loamy soil with excessively drained and deep	0.80-1.20	Road(NH-108) Settlements area

The other relevant information on study area (NH-108) regarding rockfall hazards are the traffic density and the tourist information described below.

3.2. Traffic density along the road corridor

Uttarkashi district is one of the major tourist centres in Uttarakhand state, especially during the summer and festive season. To most travellers, the NH-108 a way that leads to ancient traditions of Hinduism that flourished in its high Himalayan reaches, while for other's a way to yields opportunities for trekking, river rafting, hiking, water adventure sports. The Average Daliy Traffic (ADT) information on NH-108 is observed during the festive season for three months with different vehicle load.

Table 3-2: Average Daliy Traffic for National Highway – 108 during festive months.

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

(Courtesy- Jaganath Nayak 2010)

Table 3-3 : Statistics on tourist travelled along NH-108 from period of April 2005-March 2006.

Place	Number of visitors	
	Domestic	Foreign
Uttarkashi	84408	8212
Gangotri	87468	3440
Total	171876	11652

(Courtesy- Uttarakhand State Tourism Board)

4. MATERIALS AND METHODS

4.1. Materials

The different remote sensing and GIS derived inputs used for present study are tabulated in table 4.1 with their source and data type. The satellite data and other ancillary information are used for two main purposes for field work and preparing for inputs for rockfall modeling. The topographic map is used to identify the road, river and drainage, land cover and elevation. The Field work is assisted by various instrument used for measuring field parameters such as tree diameter, location of each trees and location of rockfall site. The various instrument used during field work are GPS, Haga-Altimeter for measuring tree-height, Laser-distance meter use to locate the distance between trees in a forest stand, metallic tape for diameter measurement etc,.

Table 4-1 : The datasets used are listed in below.

Data/Resolution	Data Type	Source
Digital topographic map No.53J/9 (1:50,000) (Restricted)	TIFF	Survey of India.(IIRS_Database)
IRS P5 CARTOSAT-1 PAN (Stereo), 2.5m resolution	Raster(TIFF)	NRSC(IIRS)
IRS P6 RESOURCESAT-1 LISS IV (MSS), 5.8m resolution	Raster(TIFF)	NRSC(IIRS)
Cartosat-DEM, 10m	Raster(*img)	IIRS
Lithological Map	Vector	NRSC(IIRS)
Soil Type and Soil thickness Map	Vector	NRSC(IIRS)
Geomorphology Map	Vector	NRSC(IIRS)
Google image, 1m	Raster(JPEG)	Google Earth
Historical Hazards record(NH-108)	Tabulated format (Excel sheet)	BRO(Border Road Organization)

4.2. Research Methods

In order to answer the research questions put in chapter first, the research methodology is developed. The research methodology is divided into three parts that is pre-field work, field work and post field work.

During pre-field work the identification potential rockfall source area were carried out along the National highway 108, using DEM-based morphometric analysis, in order to select proper rockfall site with presence of forest cover as most of the rockfall events on national high 108 are resulted from human activities like road construction, mining , blasting etc without presence of forest cover. The methodology for identification of rockfall source area is described below.

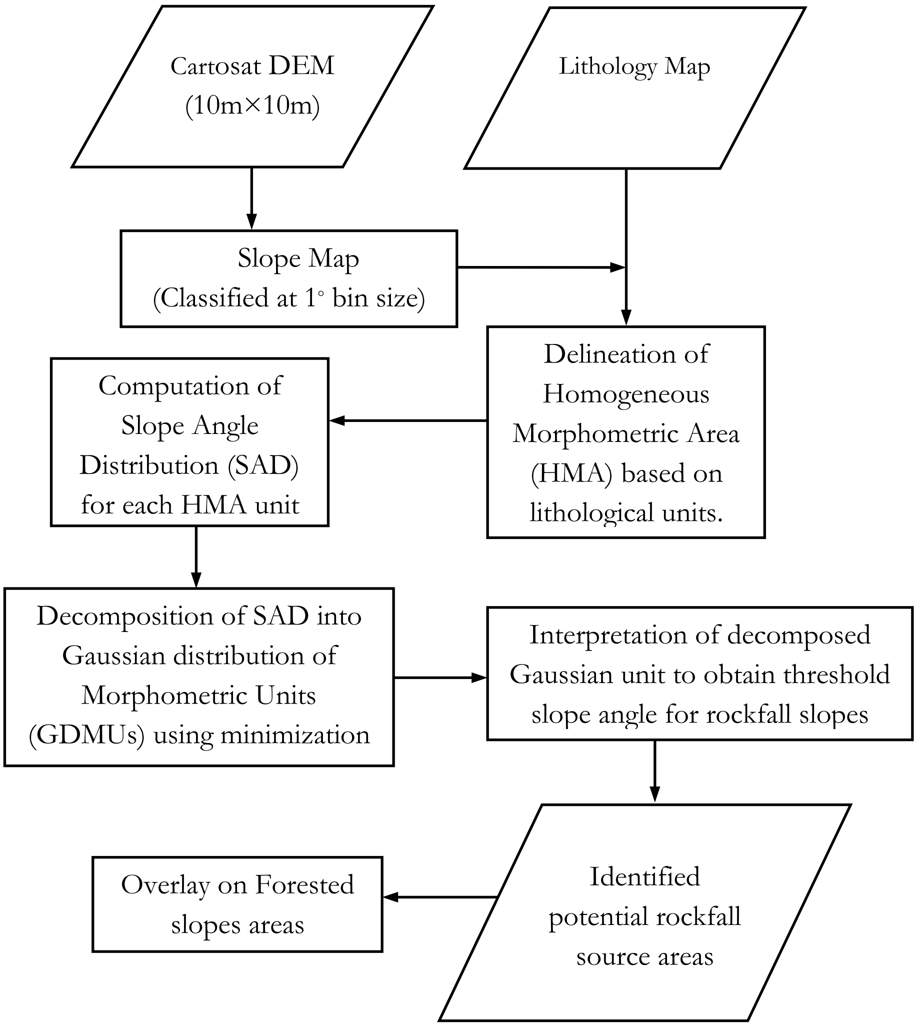


Figure 4-1: Flowchart for identification of potential rockfall source areas (Pre-field work).

4.3. Identification of potential rockfall areas (pre-field)

In order to map the rockfall susceptibility in the region, the identification of potential rockfall influence site is important. In the past rockfall areas were identified through the evidences such as talus slope and scree deposits below the cliff faces during field work and using historical rockfall inventories investigation (Hantz, 2003, Frattini *et al*., 2008). In the Literature additional methods were developed by increasing availability of high resolution Digital Elevation Models(DEM), methods were developed that combine the DEM derived slope geometry with rock type, exposition, slope curvature and land cover information in probabilistic way (Marquinez *et al*., 2003; Aksoy and Ercanoglu, 2006; Acosta *et al*., 2007). A variety of empirical, statistical and process-based approaches for detecting the rockfall source area exists, but only few of them were used for identify the rockfall source areas over a regional scale(Crosta and Agliardi 2003).

In this study a DEM-based geomorphometric approach, was used to derive the rockfall source area at regional scale on the basis of a threshold slope angle, above this slope angle the topographic units are considered potentially unstable. The main advantage of using a DEM-based approach is that it is able to detects, potential rockfall source areas located on steep slopes under forest cover as well. Further it provides a rapid and cost-effective way for identification of rockfall prone location without considering structural and lithological settings in detail (Loye, Jaboyedoff, and Pedrazzini 2009). The details of method are described below.

4.3.1. DEM-based geomorphometric analysis (overview)

First the study area was divided into so called Homogeneous Morphometric Areas (HMA), based on the similar characteristic such as uniform lithology, geology and morphotectonic. The HMAs was delineated based on the lithological units in the study area. After this, the potential rockfall initiation areas were identified by analyzing the Slope Angle Distribution (SAD) of defined HMAs. Finally the calculated Slope Angle Distribution (SAD) of each HMA units was decomposed into a Gaussian slope angle distribution which represents the specific morphological units such as cliff, steep slopes, foot slopes and plain (Strahler, 1950)
Thus the obtained Gaussian morphological units enable to extract the potential rockfall source areas. The rockfall area identified by slope angle distribution can be improved with integration of information gathered from geomorphology, topographic map and Google earth images.

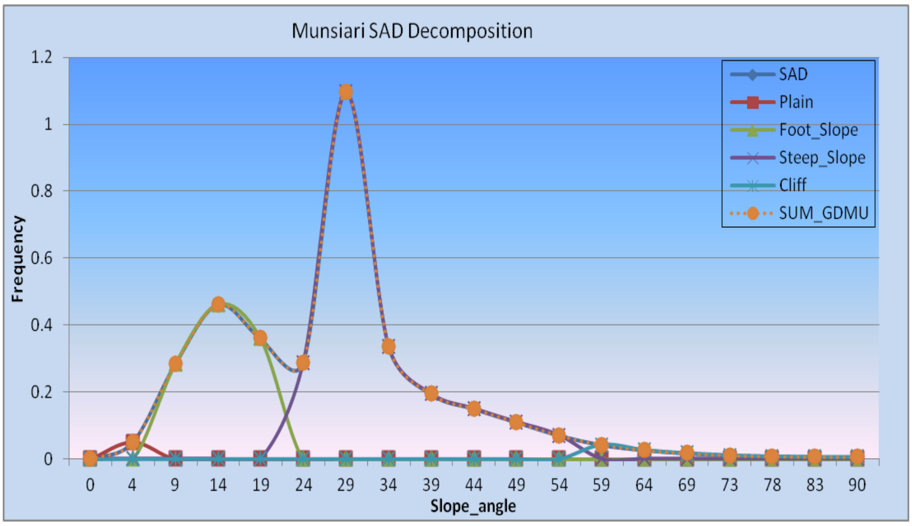


Figure 4-2: Decomposition of SAD in different Gaussian Morphometric Units.

4.3.2. Data preparation

The slope map was prepared from Cartosat DEM (10m ×10m) and classified at one degree bin size, after this the slope map were classified into Homogenous Morphometric Areas (HMA) based on the lithology of the study area. The main lithological units in the study area are chlorite schist, schistose quartzite and quartz mica, migmatite gneiss, Biotite gneiss, augen gneiss, calc-silicate gneiss belonging to various formations of Garhwal groups(see Fig4.4) (Purohit and Thakur, 1990).

The forest cover in the study area was extracted using supervised classification on LISS IV satellite data, in order to get information on identified rockfall source area under forested slope, for proper rockfall site selection during field work.

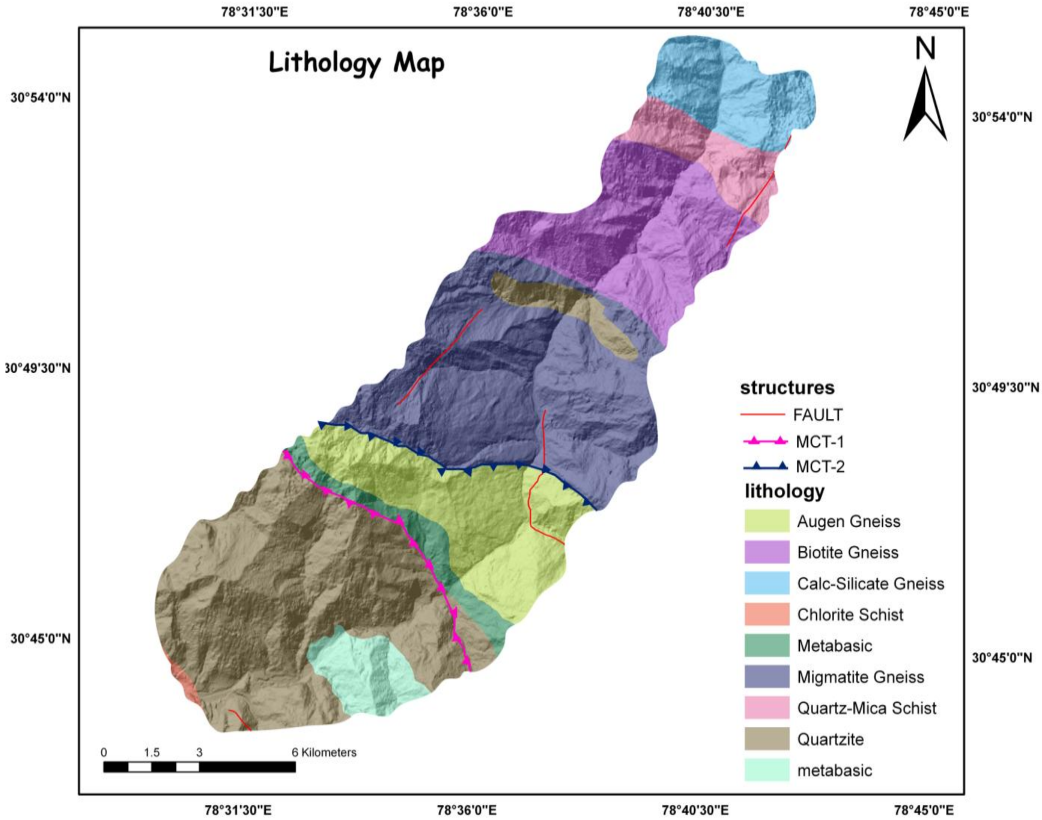


Figure 4-3: Lithology map of study area.

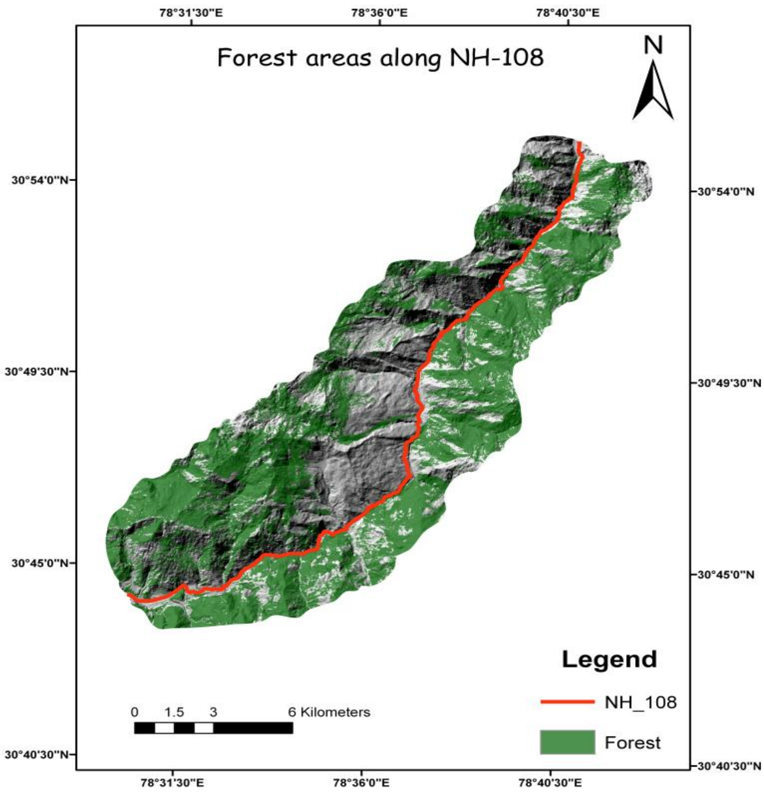


Figure 4-4: Forest and Non- forest area along NH-108.

4.3.3. Slope Angle Distribution (SAD)

It represents the frequency of slope angle distribution value for the defined HMA. The basic assumption is that the slope profile or SAD differs for two different HMA units. The frequency (ω_β) of SAD is calculated using following relation-:

$$\omega_\beta = \frac{A_{h\beta}}{A_{HMA}\, cos\beta} \qquad \text{Eq (1)}$$

Where, $A_{h\beta}$ is the sum of horizontal area of the DEM cells with same slope angle β and A_{HMA} is the total area of HMA unit considered.

To calculate the SAD frequency, the effective area of each dem cells ($A_{h\beta}$) in above equation(1) depend on it inclination or slope angle(β), as the matter of fact that surface area of steep slopes cells are less represented in comparison to flat surface DEM cells(Loye. et.al,2009). Thus in order to consider effective surface area for SAD computation each DEM cell ($10m^2$) is weighted a according to slope angle β as shown above in equation(1).

The Slope Angle Distribution (SAD) was computed in GIS environment using ArcGIS, where the above expression in equation (1) were used under spatial Analyst raster calculator or Map algebra and frequency range for one degree slope classes were generated. The frequency values for calcite-silicate gneiss lithological unit in the study area were presented in Fig.4.6.

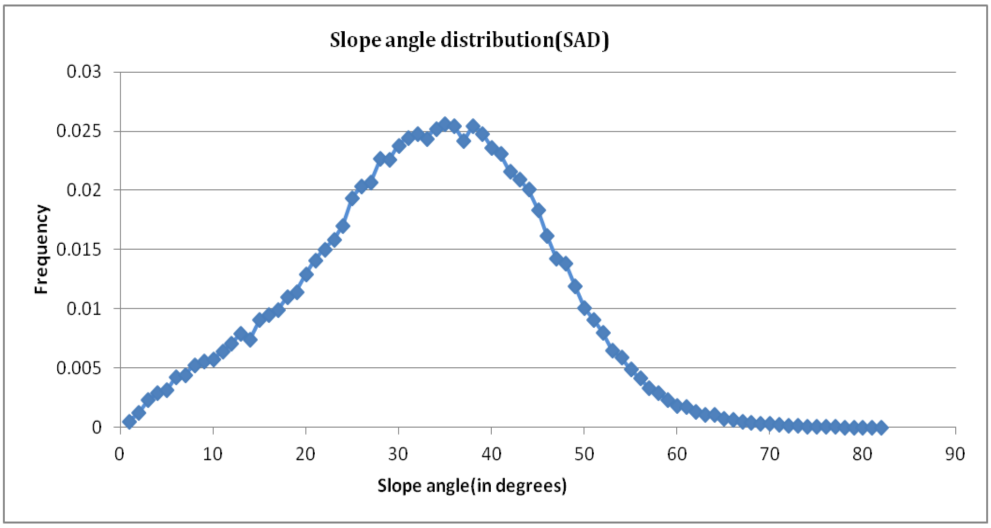


Figure 4-5: Slope angle distribution for calcite-silicate gneiss rock type (at Gagnani)

4.3.4. Decomposition of SAD

The slope angle distribution obtained in above step was decomposed into different slope angle ranges that represent different Morphometric units of topography also refer Gaussian Distribution Morphometric Units (GDMUs) as the shape of SAD is Gaussian distribution. According to Loye *et al.* (2009) general slope angle range are (0°-5°)-plains, (5°-21°) - foot slopes, (21°-54°) - steep slopes and (54°-90°)-cliffs.

The decomposition of SAD into GDMUs is done by minimizing the standard error between estimated SAD obtain by recombination of decomposed Gaussian Morphometric units and the computed SAD for delineated HMA unit.

The decomposition SAD in GDMUs is done using solver tool in Excel to perform minimization. The minimization function require initial parameter are number of GDMUs units, their estimated mean slope value and standard deviation these values are set manually based on the shape of computed SAD.

Gaussian minimization function used for SAD decomposition in solver is based on the following expression-

$$a1*\exp(-((x-b1)/c1)^2) \qquad \text{Eq (2)}$$

Where a1 is frequency of the SAD computed, b1 and c1 are the mean slope and standard deviation for desired GDMUs respectively and x is slope angle (β).

As, shown above in Figure 4-2 each decomposed Gaussian slope angle distribution is considered as a different morphological units such as plains, foot slopes, steep slopes and cliff areas. Based on the decomposed GDMUs a threshold angle is derived at the intersection (A) between the steepest morphological units, the GDMU of cliff and steep slopes. The DEM cells having slope angle more than the threshold angle value are consider potential source for rockfall, independently of local lithology and land cover(Loye *et al.*, 2009).

The potential rockfall area's obtained using DEM based approach, is improved by using geomorphology, topographic map, and matching the extracted area with hill shade map are further validated during field work. The derived potential rockfall areas were crossed with extracted forest areas obtain from supervised classification, in order to select the forested rockfall site.

4.4. RockyFor3D model

Rockyfor3D is an integrated process-based GIS rockfall model, which calculates trajectories of single falling rocks in the three dimensions. This rockfall model can be applicable for regional, local and slope scale rockfall simulations (Dorren 2011). The Rockyfor3D model is developed by Dr. Luuk K.A Dorren initially on the basis of earlier publish rockfall work on empirical and process-based modelling (Habib 1977; Azimi *et al.* 1982; Falcetta 1985; Wu 1985; Bozzolo and Pamini 1986; Spang 1988; Pfeiffer and Bowen 1989; Van Dijke and Van Westen 1990; Zinggeler 1990; Descoeudres 1997; Meissl 1998) and later with, data obtained from field and in-situ experimental investigation in the Austrian Alps (Dorren *et al.*, 2004). Since then the model is improved and validated with data from 218 real-size rockfall experiments on forested and non-forested slope in the French *Alps* ((Le Hir et al. 2004, L. Dorren et al. 2005). Rockyfor3D simulates the rockfall trajectory through a sequence of motions based on the topographic properties and type of rockfall protection measures present at the site. The conceptual sketch for movement of boulders in Rockyfor3D model is shown below.

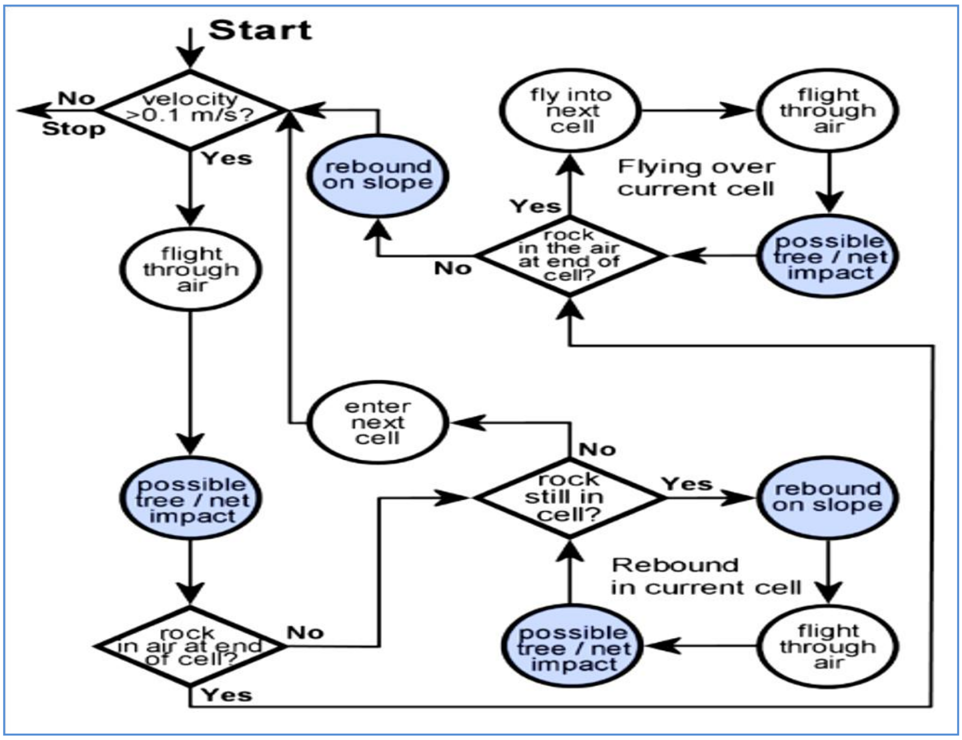


Figure 4-6: Blue indicate modelling step where change in boulder trajectory may occur. (Source- ecorisq)

The Rockyfor3D model works on the basis of complex algorithms to simulate rockfall event. This complexity of simulation process further depends on the forested and non forested scenarios. The main components of Rockyfor3D model are described below-:

4.4.1. Block form

The RockyFor3D model facilitates simulation of different block shapes-rectangular, ellipsoidal, and spherical and disc. This block shape determines the mass, volume and moment of inertia on the basis of three defined diameters (length d_1, width d_2 and height d_3). The block dimension also determines the position of block, the rebound on the slope surface and probability of impact on the trees during the simulation depends on smallest dimension out of defined dimensions. And the largest dimension was used to calculate energy loss during the impact on ground.

4.4.2. Rebound on the slope surface

The model simulates the velocity of moving boulder after the impact on slope surface, on the basis of described algorithms. Firstly the incoming velocity of falling block in the horizontal plane xy (V_{hor}) and vertical plane z (V_{vert}) is converted into an incoming normal and tangential velocity. Then, the penetration depth of the block at impact location is calculated (Pichler *et al* 2005). The penetration depth of moving boulders depend mainly on density of soil and rock mass, indentation dimensions and velocity of falling rock. The penetration depth (D_p) of the impacted boulder on the surface is depicted from shown Figure 4-7 in step 2 and 3. The penetration depth of a boulder is the important property of calculation of velocity after rebound during simulation. This is also refers as bounce and normal coefficient of restitution (R_n) that is perpendicular movement of boulder above the impacted surface.

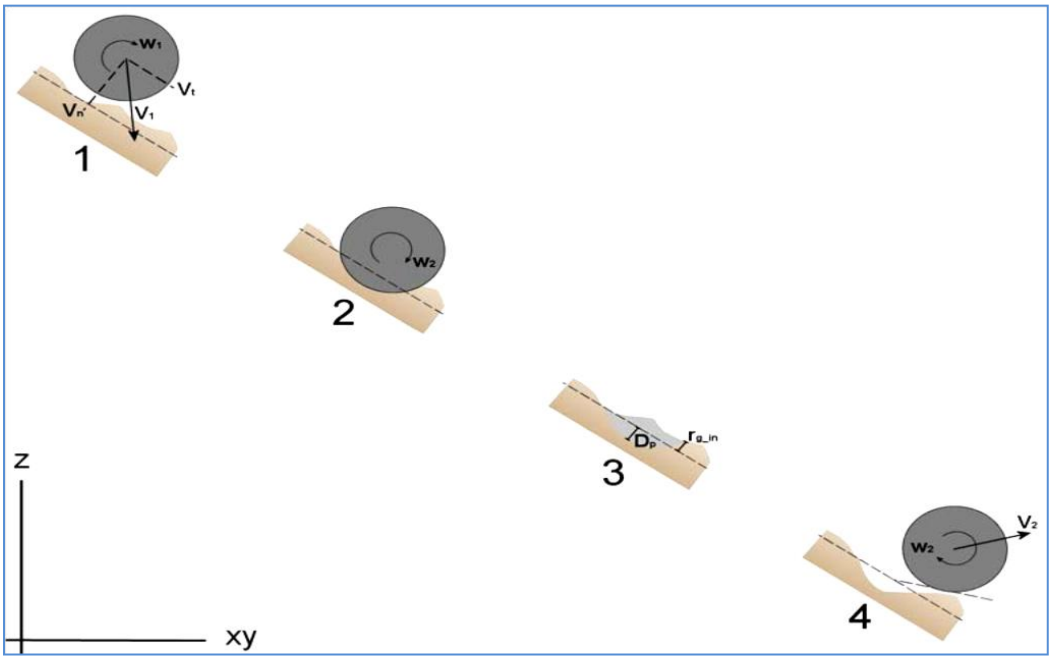


Figure 4-7: Rebound movement representation in Rockyfor3D.
(Source-ecorisq)

Another important parameter for calculation of velocity of block after rebound is the tangential coefficient of restitution (R_t) (Chau *et al*, 2002). The R_t is determined by the composition and size of material covering the slope surface and radius of falling rock itself, since the larger rocks correspond to lower effective surface roughness, compare to smaller ones (Dorren *et al* 2003). Further, (L. K. A. Dorren, Berger, and Putters 2006) proposed the following algorithm to calculate the coefficient of restitution (R_t).

$$Rt = \frac{1}{1 + (\frac{MOH + Dp}{R})} \qquad \text{Eq (3)}$$

Where, MOH is the mean obstacle height for falling boulders, due to presence of surface roughness (scree and boulders deposits etc), D_p penetration depth (m) and R is the radius of the falling block (m).After this, the R_t obtained is used for calculation of tangential velocity component (V_{t2}) after rebound as shown above, in step 4 during the block movement (Pfeiffer and Bowen 1989).

$$Vt_2 = \sqrt{\frac{R^2 * (I * V_{rot1}^2 + RockMass * V_{t1}^2) * Rt}{I + RockMass * R^2}} \qquad \text{Eq (4)}$$

Where, V_{t1} is the tangential velocity component of the block before the rebound, V_{rot1} is the rotational velocity before rebound, it depends on the initial fall height and free fall movement of block and I, is the moment of Inertia of defined block form.

Similarly the normal coefficient of restitution (R_n) is used to calculate, normal component of velocity after the rebound V_{n2} following Pfeiffer and Bowen (1989).

$$V_{n_2} = \frac{-V_{n_1} * R_n}{1 + (abs(V_{n_1})/9)^2} \qquad \text{Eq (5)}$$

Where, V_{n1} is the normal velocity component, before the rebound, $(abs\ (V_{n1})/9)^2$ is a factor to adjust the decrease in normal coefficient of restitution with increase in impact velocity before bounce, to compensate the fracturing effect of falling boulders on slope surface (Habib 1976).

Finally, the rotational velocity of moving block, based on the above normal and tangential velocity component after rebound is as follows-:

$$V_{rot_2} = min\left[\frac{V_{t_2}}{R} + \frac{(V_{t_1} - V_{t_2})}{5 * R}\right] \qquad \text{Eq (6)}$$

All, the above described model algorithms is based on the block and slope terrain interaction, while under forested scenario presence of trees, further affect the velocity, energy and movement of blocks.

4.4.3. Boulder impact against a tree

During collision with a tree, the boulder dissipates the portion of its previous incoming velocity and energy and changes the fall track direction. The amount of velocity and energy dissipation depend on the impacted position, available stem diameter and tree type (coniferous or broadleaved). The rockyfor3D model quantifies the change in energy after collision, through analytical relations developed by (L. K. A. Dorren, Berger, and Putters 2006)

$$\Delta E = -0.046 + \frac{0.98 \ + 0.046}{1 + 10^{[0.58 - ((P_i - CTA)/0.5DBH)(-8.007)]}} \qquad \text{Eq (7)}$$

Where, ΔE is the percentage of maximum amount of energy dissipated by tree depending on horizontal distance of position of impact (P_i) from Central Tree Axis (CTA) at DBH (Diameter at Breast Height).

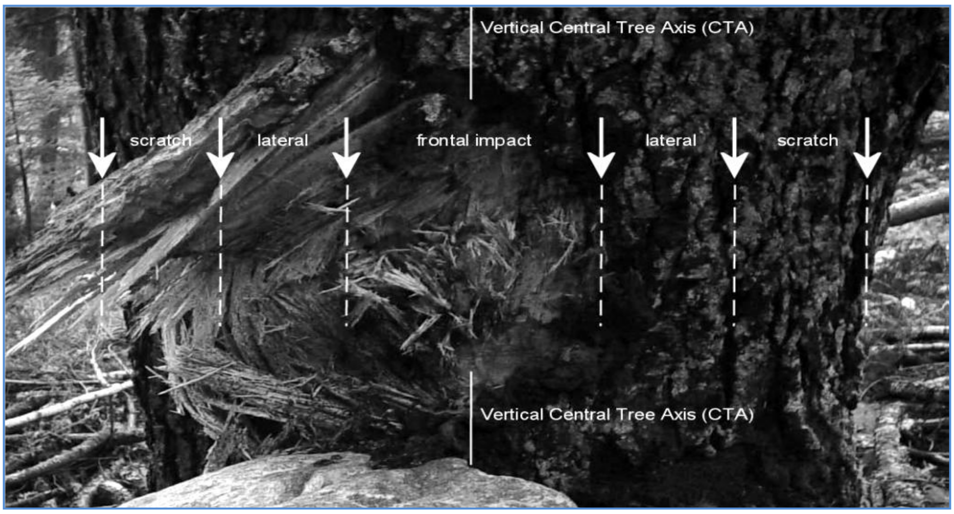


Fig.4.9: Type of impact based on the horizontal distance between (CTA and P_i) (Source- ecorisq)

The maximum amount of energy that a tree can dissipate is the function of DBH and tree type, which is as follows-

$$max.E.diss. = FE_{ratio} * 38.7 * DBH^{2.31} \quad \text{Eq (8)}$$

Where, FE_ratio is the fracture energy ratio of tree species. Rockyfor3D uses only two average values for the FE_ratio: 0.93 for coniferous trees and 1.59 for broadleaved trees.
Thus, Rockyfor3D is suitable rockfall model for present study, as it explicitly consider protective effect trees against rockfall process.

4.4.4. Model inputs

The Rockyfor3D requires minimum ten input raster maps in scenario of without forest, which includes three separate raster map for defining a boulder dimension and three maps for slope surface roughness in 70%, 20% and 10% probability classes. While for simulations with forest, model requires two additional inputs: first a tree text file containing location and Diameter at Breast Height (DBH) and second a conifer percentage raster map. All these raster map need to have same map extent and cell size (resolution). The preferred resolution lies between 2m and 10m for raster inputs ((L. K. A. Dorren and Heuvelink 2004)). All rasters should be in ESRI ASCII Grid format, which is readable by all text editors.

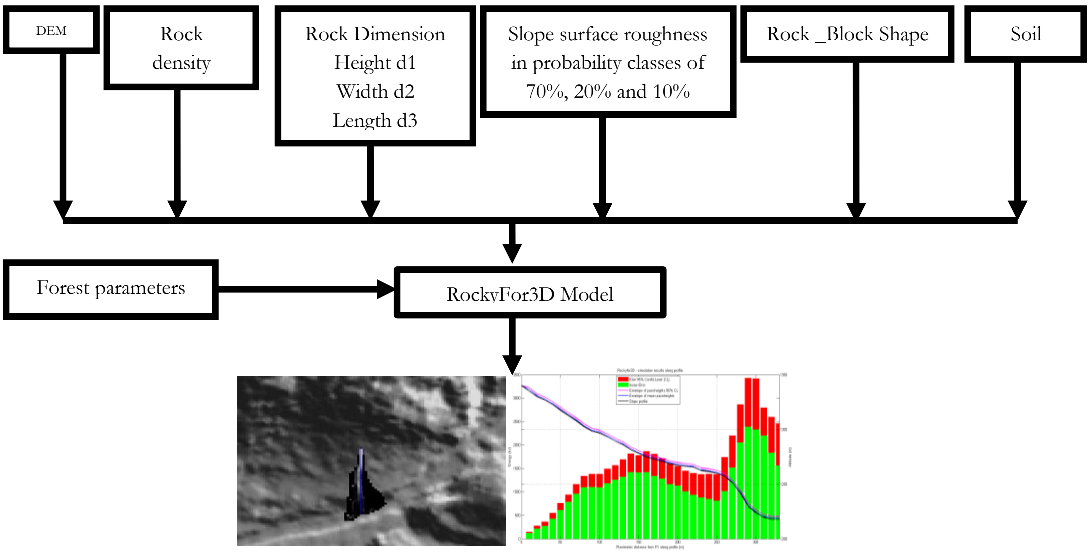


Figure 4-8: Input parameters for RockyFor3D Model

The input parameters required for RockyFor3D model are extensively field based. The field parameters are needed to be map as a polygon vector (i.e shape file) for each rockfall site with different attributes as shown in Fig (4.10). After that the created vector polygon file were rasterise each time using different attribute with same cell size and map extent.

4.4.5. Rockfall site selection (Fieldwork)

For suitable rockfall site selection (forested slope) a detailed reconnaissance survey is carried out along the road corridor as most of rockfall occur due to the road cut in the area. The priority was given to the areas identified as potential rockfall source area using DEM-based geomorphometric analysis in pre-field stage. The observation made during reconnaissance serve as a validation for identified rockfall areas. On

selected rockfall influenced slopes, acquisition of required field data such as dimension and rock type of detached block, slope surface roughness, soil type and depth, location of trees (spatial arrangement), diameter at breast height were carried out in order to assess, the rockfall hazard.
It is recommended to acquire the field parameters for rockfall trajectory simulation based slope sections such as source zone, transit zone and the deposition zone.

4.4.6. Data collection on selected rockfall sites

Different field sampling technique and methods were carried out, in order to collect the desired data. The details of the methods used to acquire different parameters are described below.

4.4.6.1. Forest parameters

In order to evaluate influence of protection forest stand on rockfall a sound database with relevant forest parameters has to establish first. The main input forest parameters required, by RockyFor3D simulation are location of each trees, Diameter at Breast height(DBH) of the trees and conifer percentage as model consider different fracture energy ratio for conifers and broadleaved tree species.

The transect sampling is done to measure the tree location and DBH of trees in forest stand. Circular plots are laid, each with radius of 10meters and area coverage of 314m² (Hoesle 2001). The plots are placed in direction to slope in order to account for the influence of rockfall process with increasing distance from source area. The distance between centres of each circular plot is 20m in slope direction, with 2m oblique from centre of above plot to the centre of next plot. The second transect can also place at the same stand; with the horizontal distance should be 20m as minimum. Further each tree inside the plots are enumerated for distance among trees in stand using laser distance meter to get the knowledge of spatial structure and measurement of tree diameter and height were measured using metallic tape and Haga altimeter respectively. In addition to these structural attributes of forest stand, parameter like tree species composition, age, regeneration pattern, underground vegetation etc were also measured.

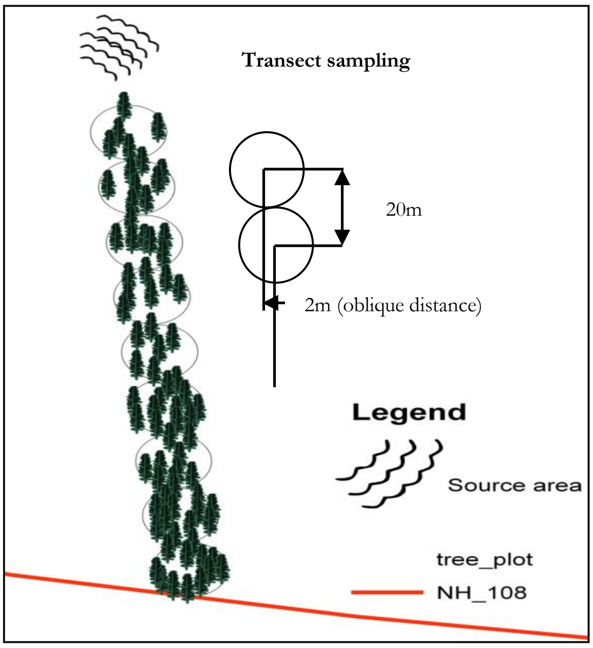


Figure 4-9: Transect sampling design.

The transect sampling also; provide an idea on the trajectories, followed by rockfall events in the past by the impact mark of boulder on trees during its down slope movement. This is important for validation of RockFor3D results as model also predicts the tree-boulder impact height which depends on the defined slope surface and soil parameter and energy of travelling block.

Both on Gagnani and Hinna rockfall site transect sample were carried out, while on site Aungi rectangular sample plot (50m × 30m) were made, because at this site trees are confined at foot of slope above the road and unevenly scattered.

4.4.6.2. Rock-Tree impact Analysis

The impact of past rockfall events on each tree were analyzed on transect sample laid down along the slope. The inspection made on transect clearly shows during rockfall event, bounce of falling blocks, leaves wounds on linear but discontinuous impacts on trees down the slope. The recorded tree impact height is used to validate the predicted results of RockFor3D model.

Figure 4-10: Observed tree-impact height (At Gagnani site)

4.4.6.3. Slope surface roughness

The surface roughness represents pieces of rock and scree deposits lying on the slope that acts as obstacles for falling block. This obstacle, results in gradual stoppage of block and affect the run-out distance during its down slope movement. The surface roughness decreases the velocity of falling blocks after rebound on the slope surface, the decrease in velocity depend on the frictional force in parallel direction to slope surface. This friction refer, to tangential coefficient of restitution (r_t) determined by composition and size of boulder or scree covering slope surface and the radius of block itself, as for large size falling rock the effective surface roughness is lower than for smaller rocks(Kirkby and Statham, 1975).

$$r_t = \frac{1}{1 + (D_{mean} / D_{rock})}$$

Where, D_{mean} is mean diameter of material covering the slope surface (m) and D_{rock}, diameter of falling rock (m).
To measure slope surface roughness and its spatial distribution at rockfall affected sites, field sampling were carried out. The sample plot of 1m×1m in transect along the slope, were laid on rockfall path in the

and scree or boulder deposit were measured in three dimension probability classes of such as 70%, 20% and 10% respectively. During field work, in two sites Gagnani and Hinna it was observed that the surface roughness on rockfall slope is located near and below the source area or release area, resulting from continuous breakage of falling rock mass on impact with slope surface. In third rockfall site Aungi huge roughness is observed, with large boulder deposit all over the slope, because of large rockfall event triggered in past.

Figure 4-11: Surface roughness measured at rockfall sites-(a) Gagnani, (b) Hinna and (c) Aungi

Table 4-2: Observed surface roughness values at three rockfall sites.

Rockfall Sites	**Slope surface roughness probability classes**		
	70%	20%	10%
Gagnani	0 m	0.05 m	0.08 m
Hinna	0.03 m	0.03m	0.05 m
Aungi	0.1 m	0.2 m	0.5 m

4.4.6.4. Soil type

The soil affects the bounce height of the falling boulders during the impact, shallow soils accounts for less bounce height as compare to deep soil, due to the more damping effect of shallow soil, resulted in more dissipation of kinetic energy of falling rocks.

The soil type is linked to normal coefficient of restitution (R_n) that affects the perpendicular to movement of boulders over the slope surface. The shallow soil corresponds to high normal coefficient of restitution compare to deep soil. The soil information for rockfall sites was obtained from the soil map of the study area provided with depth and texture properties. The soil in Gagnani is moderately shallow compare to deep soil at Aungi and Hinna rockfall sites.

The RockyFor3D model deals with eight soil types, the normal coefficient of restitution and characteristic features are described below, according to which the soil values are allotted to the affected rockfall sites. The soil types used by RockyFor model were based on the physical properties of soil like soil depth and soil textural properties which affect the normal coefficient of restitution.

Table 4-3 : The soil types used by Rockyfor3D and the related Rn values (source -ecorisq)

Soil type	General description of the underground	mean Rn value	Rn value range
0	River, or swamp, or material in which a rock could penetrate completely	0	0
1	Fine soil material (depth > ~100 cm)	0.23	0.21 - 0.25
2	Fine soil material (depth < ~100 cm), or sand/gravel mix in the valley	0.28	0.25 - 0.31
3	Scree (Ø < ~10 cm), or medium compact soil with small rock fragments, or forest road	0.33	0.30 - 0.36
4	Talus slope (Ø > ~10 cm), or compact soil with large rock fragments	0.38	0.34 - 0.42
5	Bedrock with thin weathered material or soil cover	0.43	0.39 - 0.47
6	Bedrock	0.53	0.48 - 0.58
7	Asphalt road	0.4	0.39 – 0.41

4.4.7. Simulation setting

For model simulation, first we have to define the location of rockfall source area cell and for each source cell parameters like rock density, dimension of block by three raster maps d1, d2 and d3 is defined and finally based on defined dimension block shape is calculated. If one of the cell parameters like rock density and/or dimension were not defined the DEM cell is not considered as rock fall source area.

In addition the simulation settings that can be defined to specify by user in the graphical user interface (GUI) of Rockyfor3D are:

• The block volume variation in %, meaning the percentage with which the three defined block dimensions will be randomly varied during each single trajectory simulation.

• The number of simulations per source cell, meaning the number of rockfall trajectories that will be simulated from each source cell.

• The additional initial fall height, which is the height (in m) above the DEM surface from which the block will be released initially. This allows the user to increase the initial vertical velocity of the simulated block. This value can also be helpful when using low resolution DEMs, in which small cliffs are badly represented. The default value is 0 m.

• Whether forest or rockfall net is taken into account in the simulation or not.

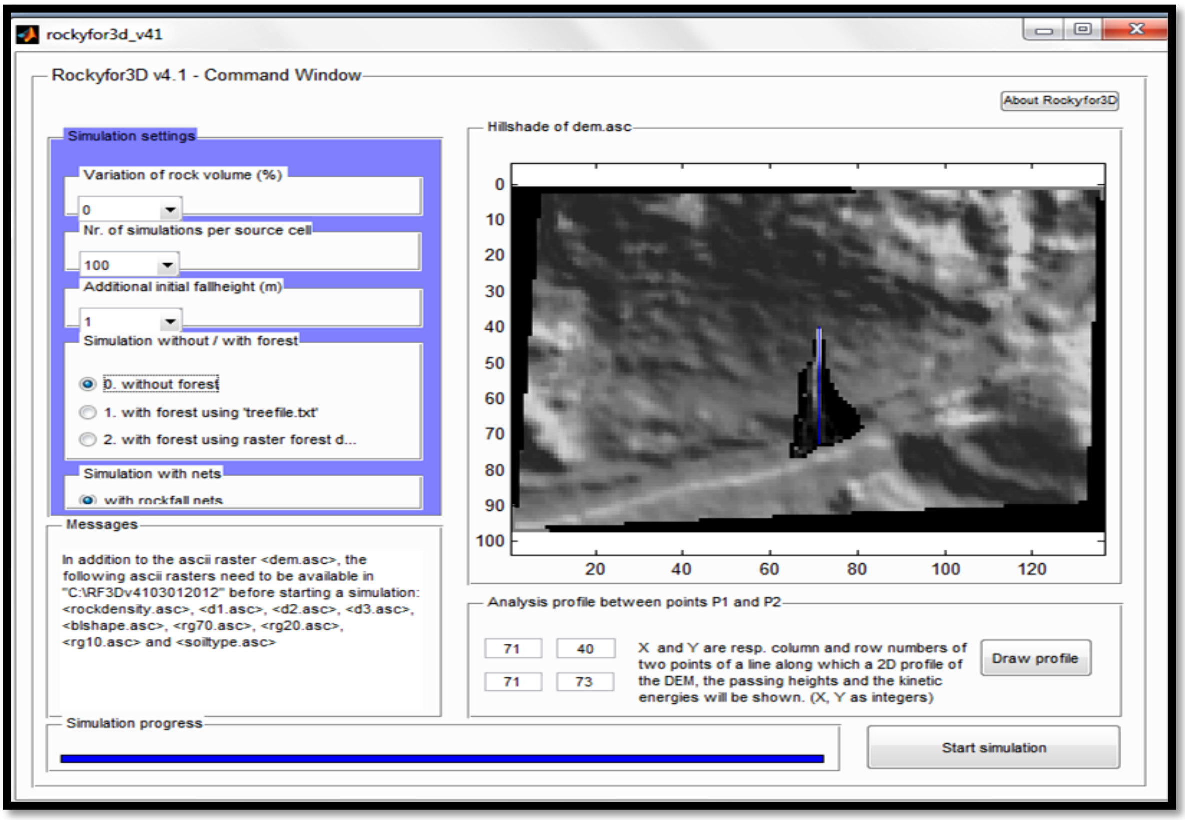


Figure 4-12: Graphical User Interface (GUI) of RockyFor3D model

4.4.8. Model Output

After each simulation, model produces different variable values in each raster cells. The outputs rasters produce by RockyFor3D are as follows-

- *E_mean*- the mean kinetic energy(translational +rotational; in KJ)
- *E_95*-the 95% confidence level of all kinetic energy values (in KJ).*(95% CL = mean value +2 * standard deviation , assuming normal distribution)
- *Ph_mean*- the mean passage height in meters(normal to direction of slope surface)
- *Ph_95*-the 95%CL of all passage height values.
- *Nr-Passage*-the number of blocks passed through each cell.
- *Nr_sourcecells*- the number of source cell, which releases rock boulders.
- *Reach probability*- (Nr_passages*100) / (Nr_simulations_per_source_cell * Nr_sourcecells) [%]
- *Nr_deposited*- The number of block deposited in each cell.
- *Rvol_deposit* - the maximum block volume (in m3) stopped in each cell.
- *Traj_time*- minimum time needed to reach a raster cell from the defined source areas [sec]
- *V_max*- the absolute maximum simulated velocity per raster cell (m/s).

In case of a "with-forest" simulation, the following two rasters are additionally created-

- *Tree_impact_heights*-maximum tree impact height per raster cell [m]
- *Nr_tree_impacts*- number of tree impacts per raster cell.

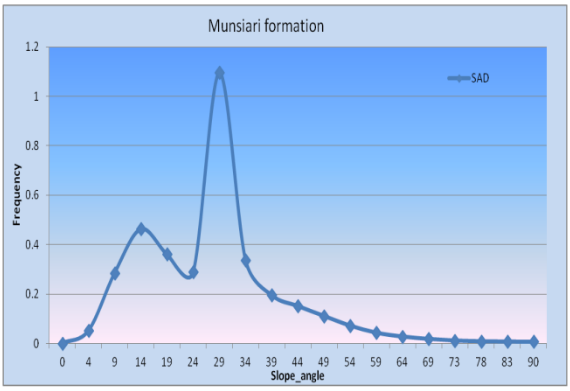
5. RESULTS AND DISCUSSIONS

5.1. Identification of potential rockfall source areas.

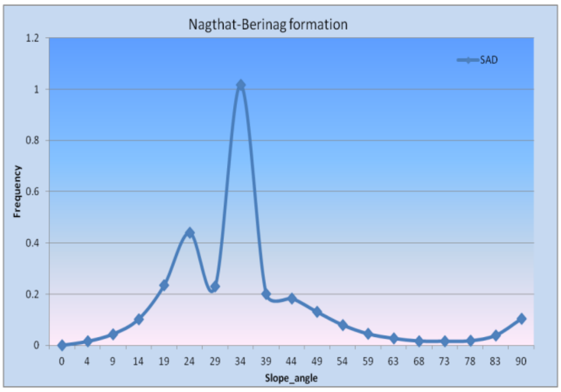
DEM-based geomorphometric analysis is used to identify potential rockfall source location in the study area. The DEM-based approach is able to identify the rockfall areas under forest cover, as it considers the slope angle of DEM cells. A threshold slope angle is derived, above which all areas was consider potentially unstable.

The Slope Angle Distribution (SAD) of each HMA units (Munsiari, Nagthat-Berinag and Ramgarh formations) was obtained, that represent varying slope angle frequency for different HMA units.

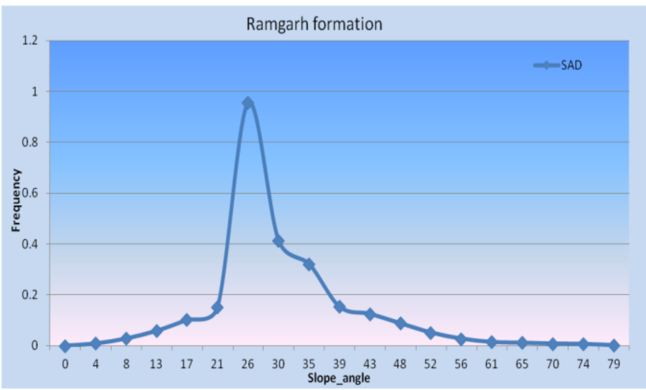
The mean slope angle of HMA units was also different for Munsiari 31°, Nagthat-Berinag 34.5° and for Ramgarh 28° respectively.



(a)



(b)



(c)

Figure 5-1: Computed SAD for HMA units (a, b and c)

The computed SAD is decomposed into different Gaussian Morphometric units (as explained earlier in chapter 4)

(a) (b) (c)

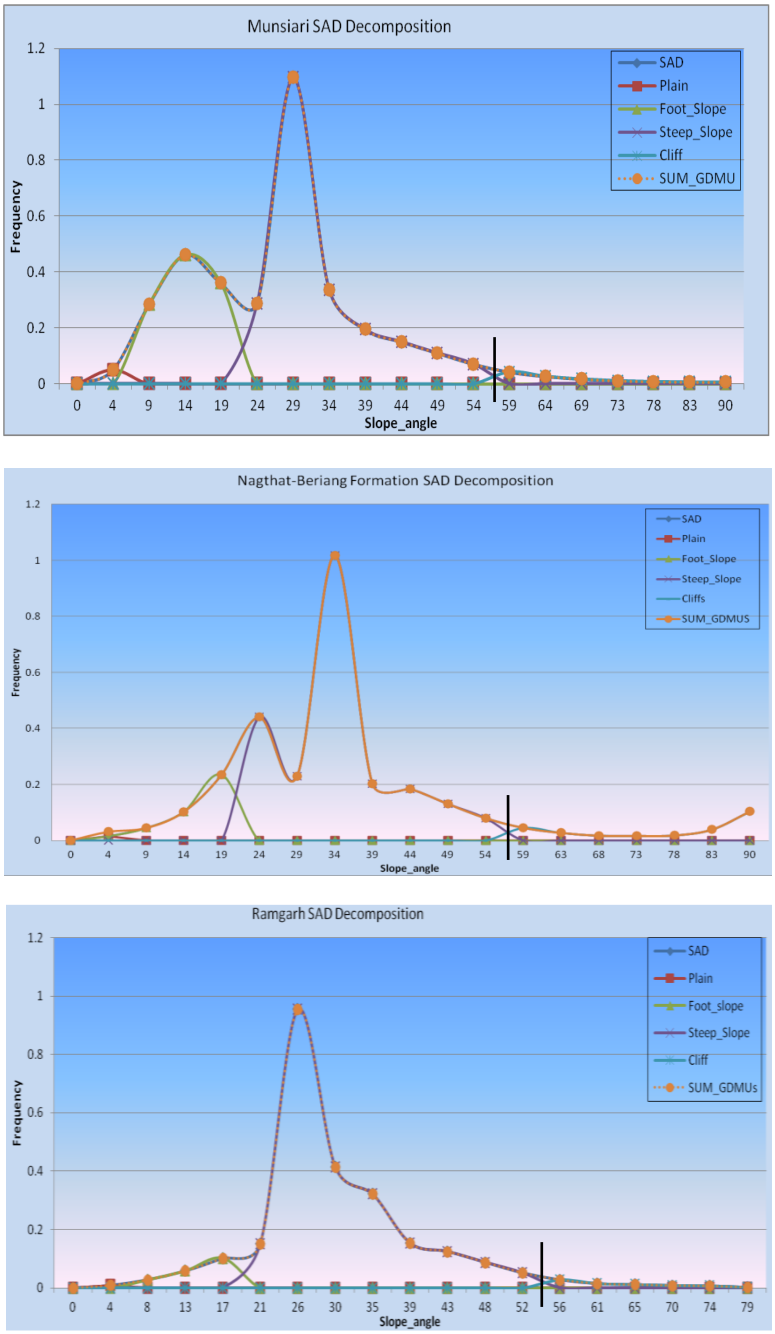


Figure 5-2: Decomposition of SAD into GDMUs for HMA (a, b and c)

A threshold angle is defined at the intersection slope angle between two steepest ‘Morphometric units' cliffs and the steep slopes. All DEM cells with slope angle steeper than this defined threshold angle are considered potentially unstable region (Rouiller et, al., 1998).

Table (5-1) shows the threshold slope angle for three morpho-tectonic units 58° for Munsiari, 56° for Nagthat-Berinag and 55° for Ramgarh with steep slope angle of 29°, 34° and 28° respectively.

Table 5-1 : Threshold slope angle for potential rockfall

HMA	Cliff_Slope	GDMU_Steep
Munsiari	58°	29°
Nagthat_Berinag	56°	34°
Ramgarh	55°	28°

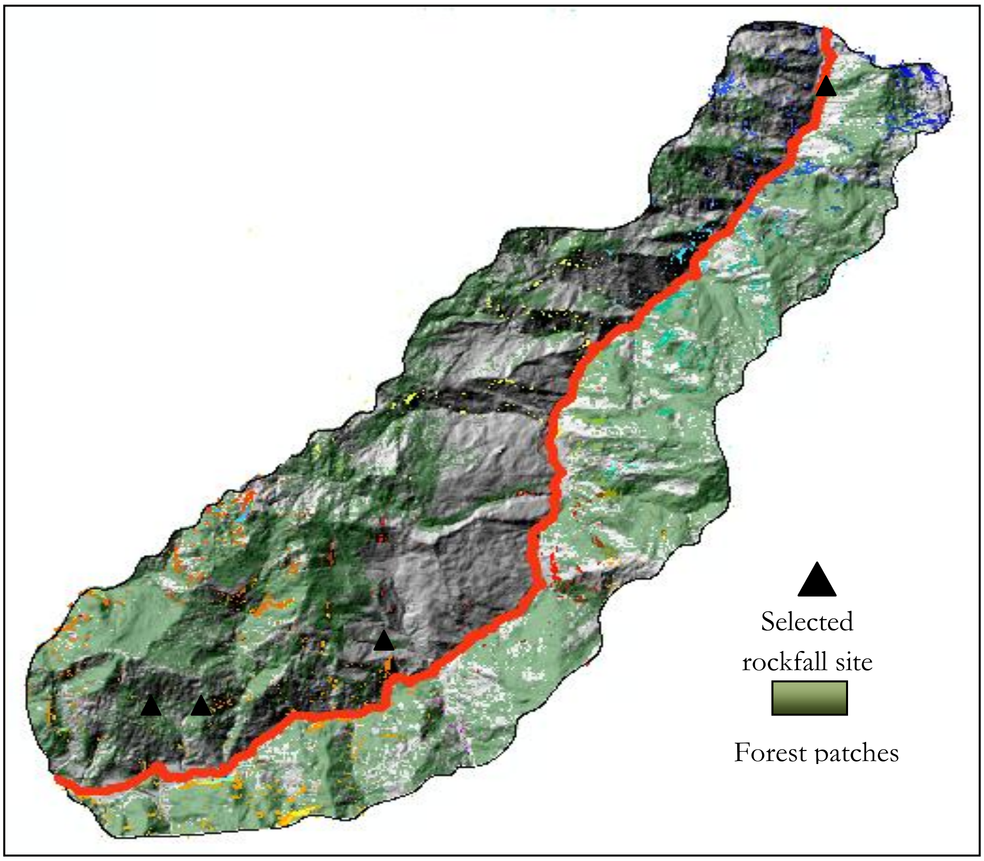


Figure 5-3: Identified potential rockfall source areas along NH-108

5.2. Quantification of protective effect of forest at different rockfall sites

The protective effect of forest stand was assessed by quantifying the change in the impact rockfall trajectories between the scenarios of current forest cover and non forest cover for different rockfall site with varying dimensions of boulders. The differences were assessed at an evaluation zone that is road (NH-108) at the foot of the slope by comparison made between the numbers of boulder passed the evaluation zone resulted from the two modelling scenarios. Thus the effect of forest is quantified by the following ratio.

$$RF_{ratio_i} = \frac{PR_{non-forested\ slope\ ,i}}{PR_{forested\ slope,i}}$$

Where, $PR_{non\text{-}forested\_slope,i}$ and $PR_{forested\_slope,i}$ are the number of rock per diameter class(i), passing the evaluation zone on non forested and forested slope.

5.2.1. Gagnani rockfall site

Table 5-2 : Assessment of protective effect stands of forest at Gagnani rockfall site.

Results of rockfall simulation Gangnani site at slope of 42°- 48°																	
Site- Gangnani																	
		Diameter of Rockfall(m)															
		0.2	0.3	0.4	0.5	0.6	0.8	0.9	1	1.2	1.4	1.5	1.6	1.7	1.8	2	2.2
Number of simulation per source cell		100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Forested	passing RF %	2	4	8	10	24	22	21	18	17	17	15	15	14	14	15	17
Non_Forested	Passing RF %	4	9	26	35	98	100	100	100	100	100	100	100	100	100	100	100
	RF_ratio	**2**	**2.5**	**3.25**	**3.50**	**4.08**	**4.54**	**4.76**	**5.55**	**5.88**	**5.88**	**6.66**	**6.66**	**7.14**	**7.14**	**6.66**	**5.88**

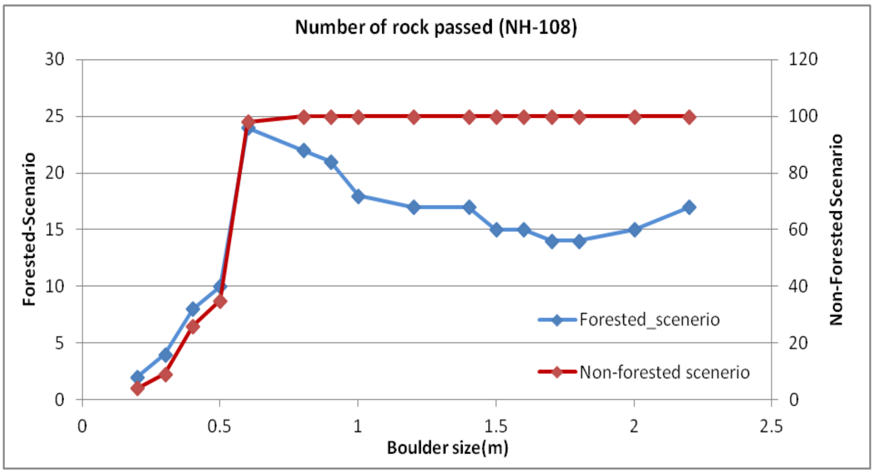


Figure 5-4: Number of boulder passed in forested and non-forested scenario at Gagnani site

The Figure 5-4 shows that, initially with small boulder size of 0.2m to 0.5m, the forest stand at Gagnani site provide less protection and slope feature like surface roughness and curvature plays an important role in stopping of falling rocks. But with increase in boulder size the effect of surface roughness decreases, as tangential coefficient of restitution is depends on the radius of falling block, for larger blocks, the effective surface roughness is lower than for smaller rocks (Luuk K. A. Dorren et al. 2004). The protective effect of forest stand increases, due to the increase in tree-impact probability of boulders with increase in the size of rock.

Thus, RF-ratio shows a good correlation with protective function of forest against rockfall hazard, as it excludes the role of surface roughness and soil damping and only contributes for protective effect of forest.

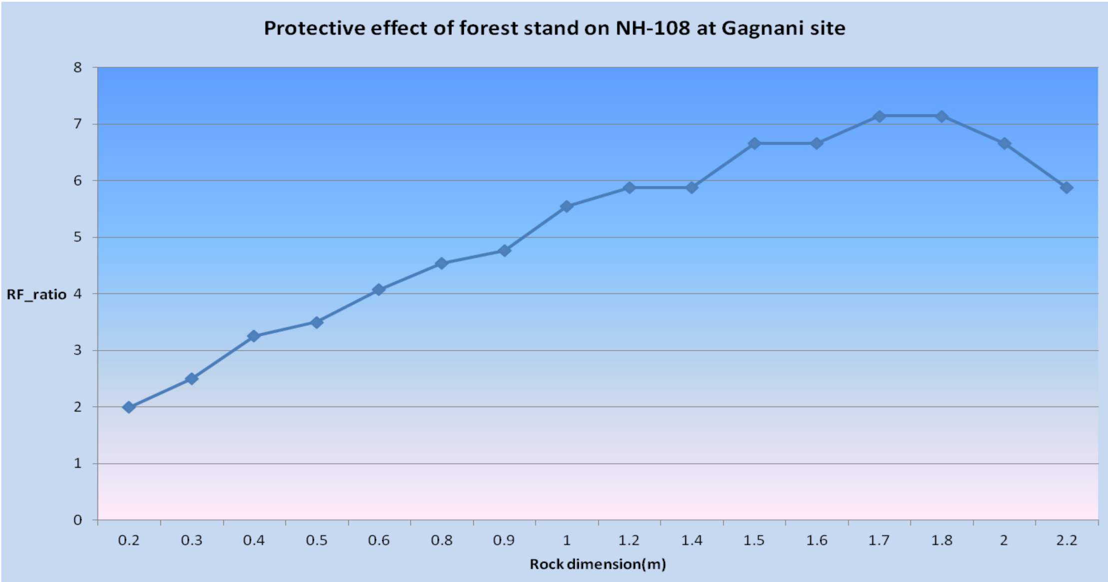


Figure 5-5: Protective function of forest at Gagnani (NH-108)

The graph in Figure5-5 shows the protective effect of forest stand structure against the varying sizes of rock blocks. This clearly implies that at the Gagnani site the forest is more protective for boulders of moderate size i.e (0.6 to 1.8 m) as for this R.F ratio value increases continuously from 4.08 to 7.14, after that the R.F value again decreases for boulder with >2m diameter. This is due to increase in the potential and kinetic energy of boulders with an increase in mass and volume as compared to the boulders with small sizes, the kinetic energy of moving boulder were further enhanced by the slope i.e above 45° and elevation difference of 250 meters from source area to foot of slope at Gagnani site. The protective effect of forest against boulders also, depends on the arrangement, spacing and stem density of trees and also on the forested slope length and the distance of evaluation zone from source area of rockfall.

5.2.2. Hinna rockfall site

At Hinna rockfall site, the protective function of forest gradually decreases with increase in the rock dimension, fig 5.3 shows maximum protection accounts for boulder of 0.50 m with RF_ratio of 10 and minimum protection for 1.2 m with RF_ratio value 5. The decrease in protective function with increase in rock dimension resulted because the forest stand at Hinna is not very mature and the mean diameter of tree in stand were 68 cm on lower side comparing to other two sites 125 cm and 258 cm for Gagnani and Aungi respectively.

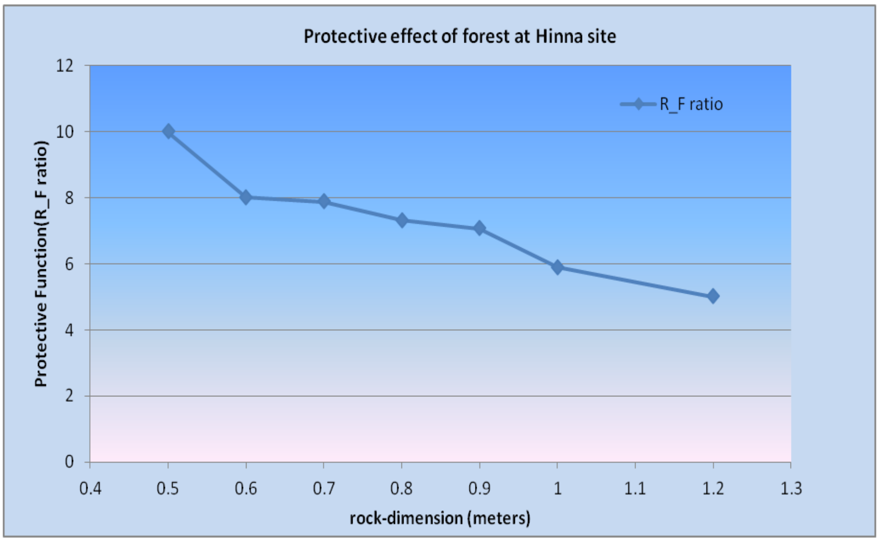


Figure 5-6: Protective function of forest at Hinna

The stand density at Hinna were high 828 stem per hectare correspond to less distance between the trees. Thus provide high protection for the smaller dimension blocks. (L. Dorren et al. 2005) also reported that for smaller rocks, smaller trees are required to increase the impact probability. But at the same time for bigger rocks, bigger trees (with high DBH) are required to stop the rock coming with high kinetic energy and velocity.

5.2.3. Aungi rockfall site

The protective function of forest at Aungi rockfall site increases with increase in boulder size up to 1 m after that protective effect decreases with increase in the rock dimension. The forest stand at Aungi was unevenly scattered with low stand density, but as Aungi is an ancient rockfall site, the slope surface was characterized by huge boulder deposit of 20 to 50cm. Therefore the small dimension boulder was easily stopped by high roughness, resulting in lower number of boulder passed through the evaluation zone i.e (NH-108).

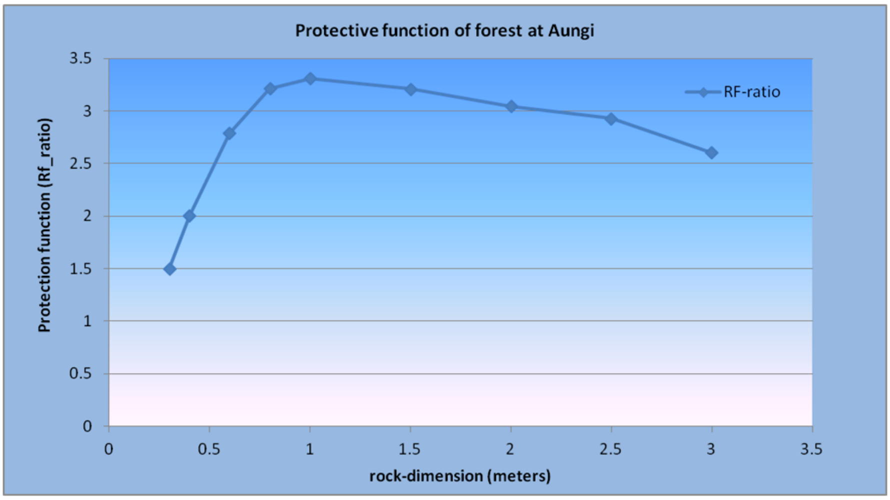


Figure 5-7: Protective function of forest at Aungi

5.2.4. Number of Tree-boulder impacts

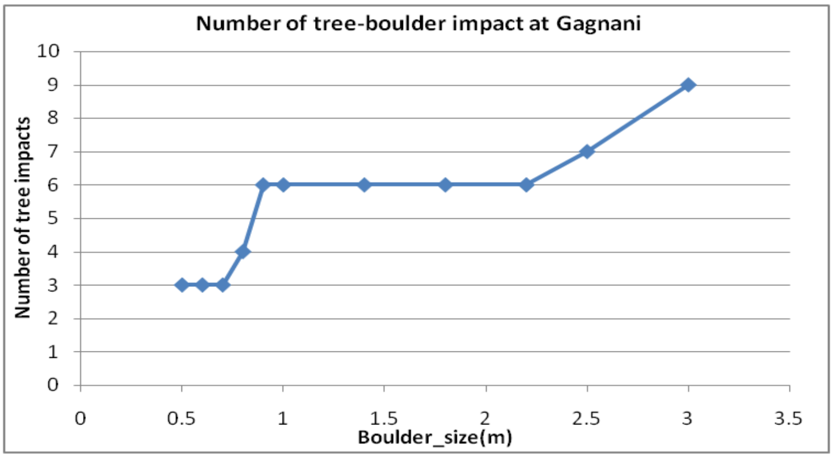


Figure 5-8: Number of tree impact against boulder size

The above graph (fig 5-5) shows the general increase in tree impact probability with increase in boulder size. But the impact probability show no change for small change in boulder size from 0.5m to 0.7m, and with sudden increase for 0.8m boulder, followed by gradual increase in impact probability for boulder size of 2.5 m and more.

This rapid change in impact probability depends on the stand density or distance between two trees in forest stand. Moreover the forest stand at Gagnani site is natural, with uneven spatial distribution of trees, with mean free distance between tree were greater than 2m observed during field investigation, so boulder with small size have low probability of impact. Therefore, for large size boulders forest shows higher impact probability compare to low size boulders.

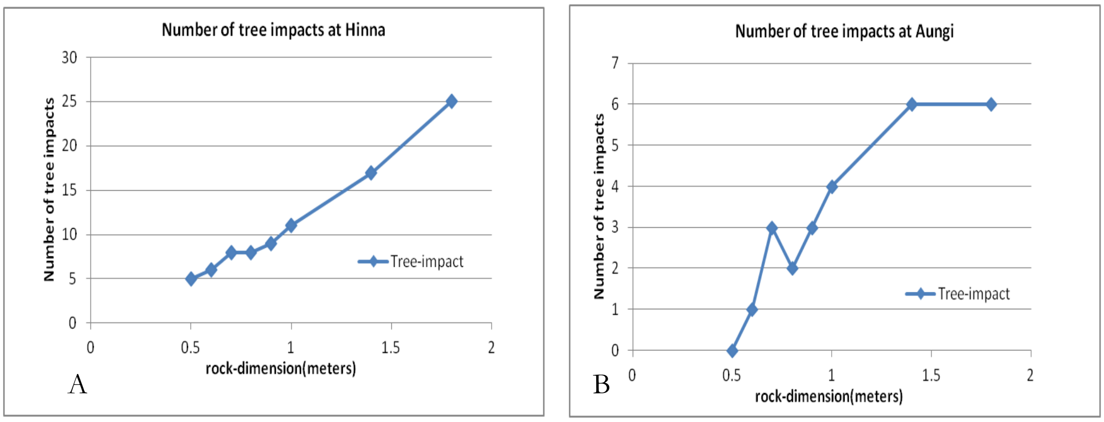


Figure 5-9: Number of tree impacts at Hinna (A) and Aungi (B)

The graph in fig (5-6 A) shows that the number of tree impacts at Hinna continuously increasing due to high tree impact probability for Hinna site because of high stand density. While in graph (B) the probability of impact increased but not gradually for Aungi site due to low number of trees in the stand.

.

The fig 5.7 shows simulation maps for one meter boulder size the run-out probability under two different scenarios. The probability of boulder crossing the NH-108 is on higher side under non forested condition compare to the non forested slope.

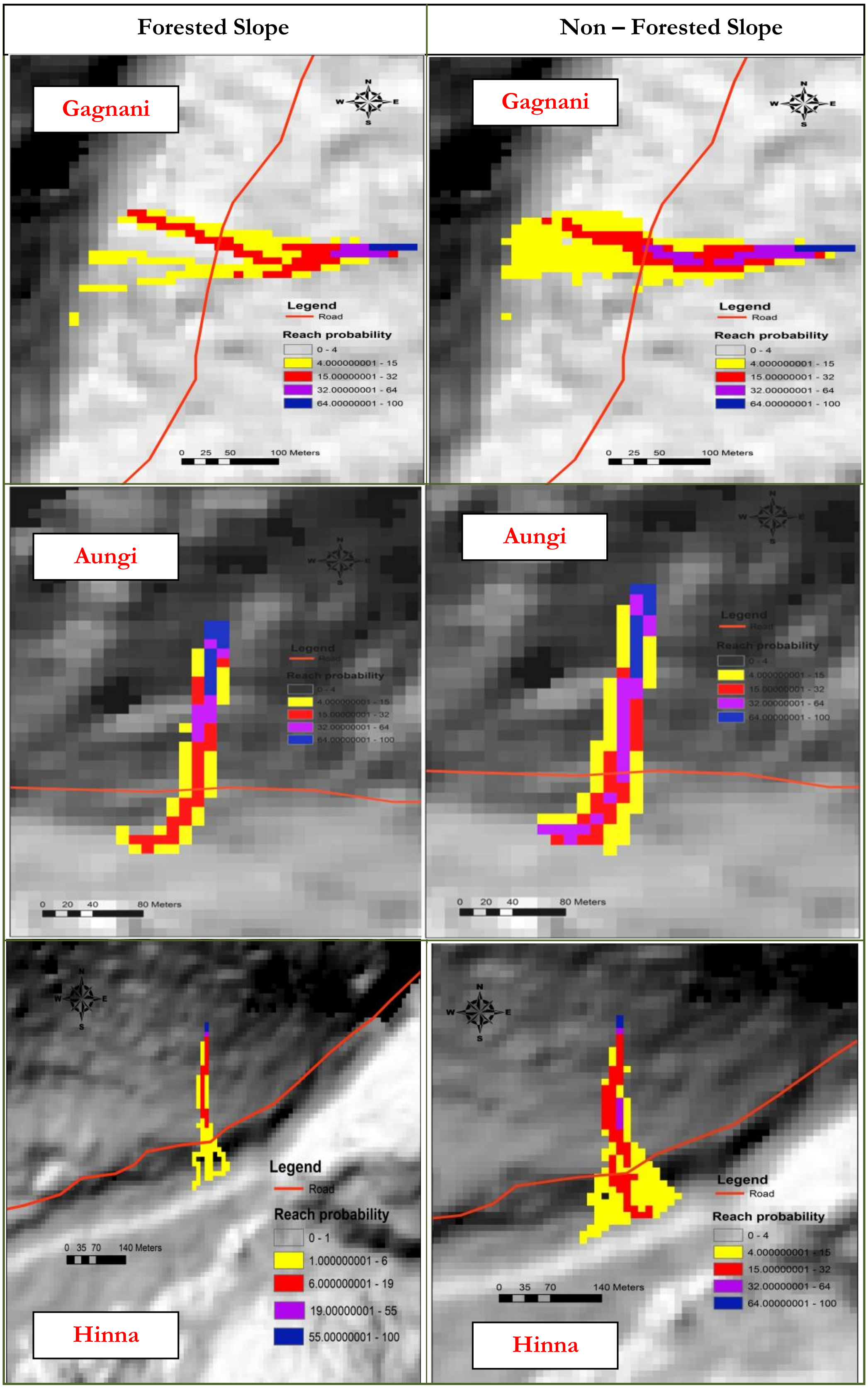


Figure 5-10: Comparison of reach probability of trajectories at three different rockfall sites (1m boulder)

5.3. Impact of lithology on protective function of forest

The model simulation shows that lithology in general does not affect the protective function of forest of in great deal. The model was simulated for different major lithological units present in the study area, under the same forest density, elevation zone and boulder shape and dimension (0.50m) to assess its role of varying lithology in protective function. RockyFor3D model consider variation in lithology in terms of rock-density of falling boulders. Based on the density of falling rock mass model predicts, the bounce height, kinetic energy and velocity of falling of rock trajectory which are important parameter to assess protective function of forest.

Different rock type like Quartzite, Quartz-mica-schist, Calcite-Silicate Gneiss and Amphibolite with rock density of 2300, 2500, 2800, 3200Kg/m^3 respectively are used. Lithology or rock type mainly affects the protective function of forest by the magnitude and frequency of rock released from particular lithological unit, which depends on the size, density, orientation and continuity of rock discontinuities (Hoek & Bray 1981, Goodman & Shi 1985). During field investigation it was observed that at Gagnani site where, the Calcite-Silicate Gneiss is rock type the magnitude of rock released is less compare to Quartzite at Hinna rockfall site where large number of big size boulder were found due to past rockfall event.

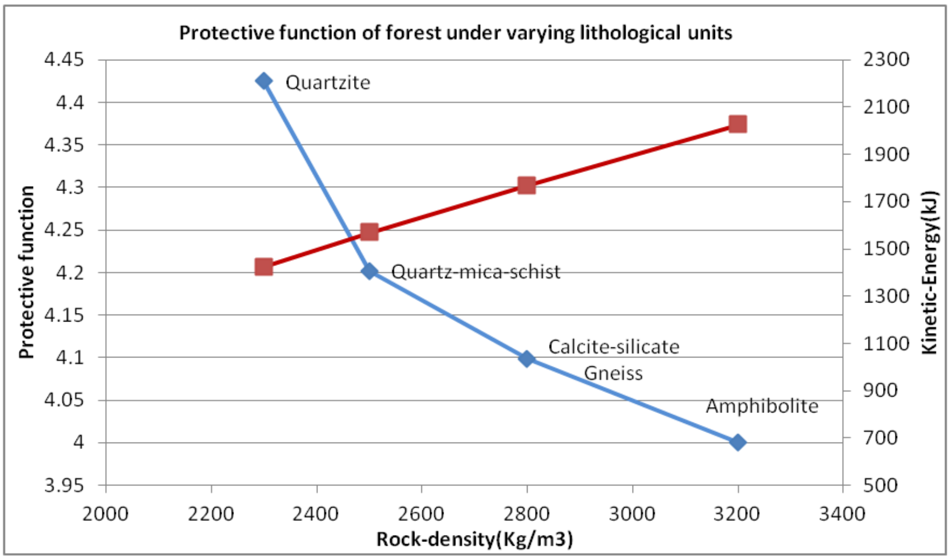


Figure 5-11: Protective function of forest under varying lithology.

The above graph shows that with increase in rock density from quartzite (2300Kg/m^3) to Amphibolite (3200Kg/m^3), the protective function of forest decreases, as with increase in rock density results increase in the momentum and kinetic energy of falling rock and retarding factors like surface roughness, become less effective on the moving block results in longer run-out distance. Therefore, more number of trees is required in forest stand to reduce the velocity component of falling boulders. On the other hand the impact of different rock-type or lithology on the protective function of forest can also be depicted from kinetic energy of falling boulder under forested scenario which, shows kinetic energy of moving boulder increases with rock density, due increase in mass per unit volume of rock sample.

The difference predicted in the protective function of forest under different lithological class, clearly indicates that the protective function of forest mainly depend on the tree density and spatial arrangement of trees in a forest stand irrespective of different lithological units. The rockfall ratio (RF) for different lithological units are 4.42(Quartzite), 4.20(Quartz-mica schist), 4.09(Calcite-silicate gneiss) and 4 for (Amphibolite).

To analyse the impact of different forest type, spatial arrangement and diameter distribution of trees on a lithology unit, simulation is carried by changing the original (Chir pine) forest stand at Gagnani site with other two rockfall sites, was Aungi where broad leaved Toona forest is present and Hinna where same Chir pine (conifer) but with comparatively higher stand density is present.

The results shows the rockfall ratio (RF) is 2.22 for Aungi trees and 2.32 for Hinna forest at Gagnani site while the original (RF) value is 5.55 the variation in RF value account for the distance between rockfall source area and forest location and also on forested length of the slope. The difference in RF value for Aungi in comparison with Hinna forest is not much because the mean diameter for Aungi forest (200cm) is much more compare to Hinna (68cm), despite the fact the only 42 (*Toona ciliata)* trees are located along 80m forested length above the road and for Hinna stand at Gagnani the forested length is 110m compare to actual forested length of 200m from source to national highway with mean diameter of 125cm at Gagnani. Moreover, the energy dissipation potential of broadleaved trees (*Toona ciliata*) are more 1.59 compare to conifers (pine) 0.93(Dorren and Berger2006).

5.4. Optimum stand density for rockfall protection

The optimum stand density of forest for rockfall protection were analysed on the basis of dominant dimension of fallen boulders deposited at the base of slope investigated during the field work at three different rockfall sites. Both forest stand density and dimensions of falling block, decide the level of protection provided by forest against rockfall hazard, because it affects the probability of tree-boulder collision.

For Gagnani rockfall site, the protection provided by current forest cover was 2.5 RF (Rockfall ratio) with 223 stems per hectare and the dominant boulder size of 0.50 m. The optimum stand densities for rockfall protection at Gagnani site were assessed against boulder (0.50m) through model simulation. The forest stand density was increased by adding trees to each field sampled existing plots and then the protective effect of forest were assessed by estimating (R.F) ratio.

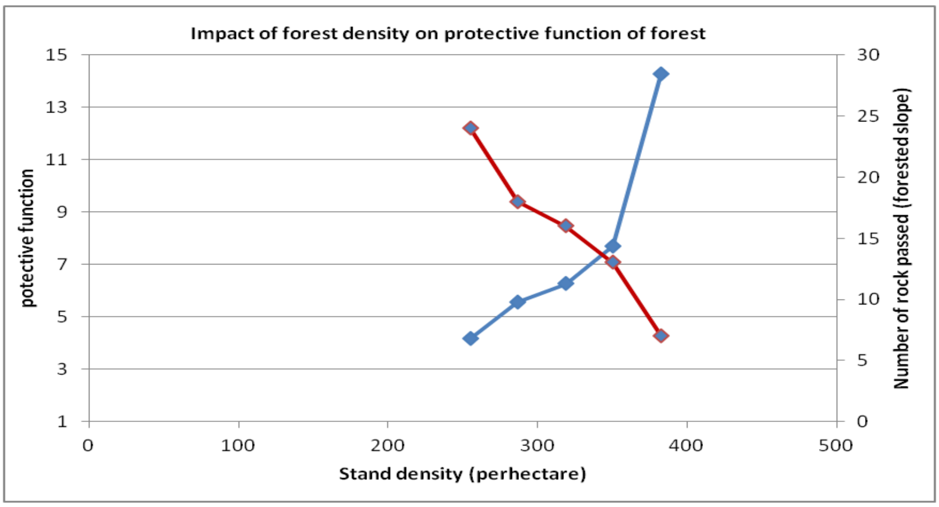


Figure 5-12: Protective function of forest at Gagnani site with different stem densities.

The model simulation results shows that with increase in the stand density of forest, the number of boulder (0.50cm) reaching down the slope were continuously decreasing and making forest more protective against the falling rock. The above graph shows that the optimum forests stand density for Gagnani rockfall site is more than 300 stems per hectare with a mean diameter of 125 cm and the value for RF_ratio were above five.

Frehner et al, 2005 provide management guidelines for protection forest against rockfall and found that optimum stand density of protection forest, for the boulder size of 40cm to 60cm were ≥ 300 stems per hectare with mean DBH of more than 24cm(explain above table).

The simulation results at Gagnani rockfall site shown that forest of stand density of 300 stem per hectare or more will provide effective protection against rockfall, for boulder size 0.50cm or bigger. The present forest cover at the site with stem density of 223 stems per hectare and mean DBH of 125 cm are more effective for block dimension of more than 0.50 cm and the block dimension of 0.50cm or smaller were quite often passed through the forest cover and deposit at the bottom of the slope.

5.5. Accuracy assesment of RockyFor3D model

The reliability and quality of input data for proper rockfall modelling were assessed on the basis of observed and simulated rockfall pattern, with spatial distribution of rockfall trajectories, run-out distance and the mean impact height of boulder on the trees.

The accuracy assessment of model simulation results was carried out by comparing the measured mean tree impact height of boulder on tree during field work and the simulated tree impact height by RockyFor model. The past rockfall event leaves the wound or scar marks on the impacted tree stem. To compare simulation results with empirical or observed values, arithmetic mean of the each cell that accounts for the simulated tree impact height were taken into account and in subsequent step, the mean error and root mean- squared errors(RMSE) between predicted and observed number of impact height were calculated.

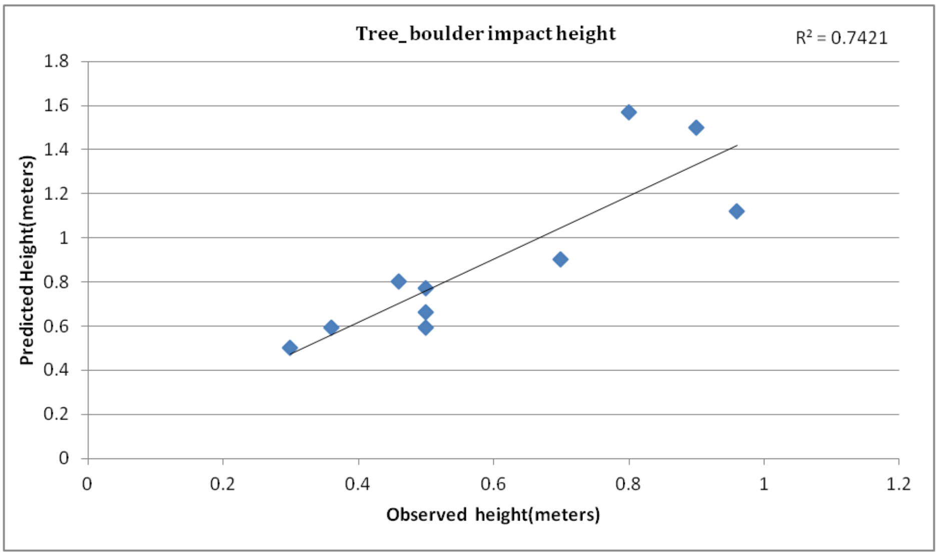


Figure 5-13: Tree-boulder impact height observed v/s predicted

For Gagnani rockfall site, the observed mean impact height was 0.89 m compare to predicted impact height of 0.59 m, the RockyFor3D shows underestimation in the mean tree impact height by Mean Error of -0.30 m and root mean square value 0.36 m for dominant boulder size of 0.40 m to 0.60 m.

The main factors responsible for the difference predicted and estimated mean impact height of tree-boulder are low spatial resolution of DEM (10m×10m), unable to detect the micro relief terrain parameter that affects the velocity of falling rock, for instance huge deposit of ancient rockfall at the slope, the affect bounce of boulder, could not be included in coarser DEM resolution (Dorren, 2011).

The soil damping property is also important factor that influence the mean impact height of boulder as the soil parameter defined for the site is deep and fine soil resulted in more normal coefficient of restitution, compare to the actual soil condition, resulted in underestimation of impact height.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1. Conclusions

In the present study, the protective function of forest against rockfall hazard is assessed using a probabilistic process based GIS model. The outcomes of the study showed that the forest stands are effective in mitigating the impact of rockfall hazard. Furthermore, the model also simulated the optimum forest stand density of the protection forest to offer maximum resistance against rockfall hazard. The model also simulated the tree impact height of falling boulders which matches closely with the tree impact height as observed in field condition. This proved the repeatability and transferability of the model in Himalayan settings. Hence this work was successful in meeting all the proposed objectives and answers the associated research questions raised.

Research Question 1: How to map potential rockfall source area under forest cover?

Answer: The DEM based geomorphometric approach is used to identify the potential rockfall sources in the study area. The result predicted the potential rockfall sites in the study area based on slope angle distribution of different geomorphometric units. The filed observation proved that the identified areas as predicted by this method related with the field rockfall sites. The prediction can be further improved by integrating lithology information and use of high resolution DEM.

Research Question 2: How protective effect of forest stands can be assessed against down slope vulnerable features?

Answer: The protective effect of forest is assessed by simulating the model under non-forested and forested scenarios and calculating the rockfall ratio (RF) of number of passing boulders in these two situations. The RF ratio of non-forested to forested scenarios so obtained from the simulation results for 1 m boulder size at three rockfall sites considered in this study are 5.55, 5.88 and 3.31 for Gagnani, Hinna and Aungi respectively. The higher RF for Hinna shows that the number of boulders passed the evaluation zone (NH-108) is lower as compared to non-forested condition, hence the higher values followed by Gagnani and Aungi. Therefore, it can be inferred that the RF ratio can be used as a decision parameter for assessing the protective effect of forest stand against rockfall.

Research Question 3: How lithology of the study area affects protective function of forest against rockfall?

Answer: The simulation result of the model showed that the lithology of the study area has no significant impact on protective function of forest against rockfall. This is deduced from the fact that no significant change in RF ratio is observed with varying lithology as evident from RF values of 4.42, 4.20, 4.09 and 4.00 for Quartzite, Quartz-mica schist, Calcite-silicate gneiss and Amphibolite respectively.

Research Question 4: What should be the optimum stand density of protection forest for minimizing the impact of rockfall hazard?

Answer: Considering simulation outcomes of different stand density at Gagnani rockfall site resulted in optimum stand density of > 300 stems for maximum possible protection against rockfall hazard. This stand density is optimized for boulder size range of (50 – 60) cm which is the predominant boulder size observed at Gagnani.

Research Question 5: Are the condition and data requirement are sufficient for the proper rockfall modelling using RockyFor3D model in the study area?

Answer: The condition and data requirements are sufficient for proper rockfall modeling as inferred from the outcomes of the simulation study. Most of the input parameters such as tree location, DBH, fallen boulder dimension and slope surface roughness for the model simulation are field based, and hence that can be derived from field observation. The input DEM determines the slope and fall track of the boulders. The spatial dependency of simulated rockfall trajectories were found to be correlated with observed trajectories during field work. Therefore, it can be deduced that the RockyFor3D model is valid for the study area.

The results of the study was influenced by several factors such as medium resolution of DEM used which may have resulted in variation in bounce height of the boulders and probable trajectory of the falling boulders. The prediction can be improved by the use of high resolution DEM.

6.2. Recommendations

All the future studies carried out based on the present research theme should consider the following issues for improving the simulation results.

- The scale of applicability of the model is limited by availability of the forest stands parameters. As the Himalayan region is quite inaccessible for conducting field inventories for forest stand parameter data collection. Hence, future investigations should focus on some earth observation technique to derive input forest stand parameter for extending the use model on regional scale.
- Use of LiDAR DEMs for achieving more accurate simulation results is recommended.
- More representative studies are required to establish the importance of protection forest in mitigating the impact of rockfall hazard in Himalayan region.

LIST OF REFERENCES

Acosta, E., Agliardi, F., Crosta, G. B., and R`ıos Aragu´es, S. 2007: Regional Rockfall Hazard Assessment in the Benasque Valley (Central Pyrenees) using 3D numerical Approach, *Tech. rep., Project* DAMOCLES.

Aksoy, H. and Ercanoglu, M. 2006: Determination of the rockfall source in an urban settlement area by using a rule-based fuzzy evaluation, *Nat. Hazards Earth Syst. Sci.*, 6, 941–954

Azimi, C., Desvarreux, P., Giraud, A. and Martin-Cocher, J., 1982. Méthode de calcul de la dynamique des chutes des blocs - Application à l'étude du versant de la montagne de la Pale (Vercors). *Bull. Liais. Lab. Ponts Chauss.* 122: 93-102.

Bozzolo D. and Pamini R., 1986. Simulation of Block Falls down a valley side. *Acta Mech.* 63: 113-130

Brang, P. 2001. "Forests as Protection for Natural Hazards." In *Forest Handbook*. J.Evans publication.

Chau, K.T., Wong, R.H.C. and Wu, J.J., 2002. Coefficient of restitution and rotational motions of rockfall impacts. *Int. J. Rock Mech. Min. Sci.* 39: 69–77.

Corominas, Jordi, Ramon Copons, Jose Moya, Joan M Vilaplana, Joan Altimir, and Jordi Amigo. 2005. "Quantitative Assessment of the Residual Risk in a Rockfall Protected Area" 2 (4) (December): 343–357. doi:10.1007/s10346-005-0022-z.

Cruden, D.M., and D.J. Varnes. 1996. "Landslide Types and Processes." *Landslides-Investigation and Mitigation, Special Report* 247: 36–75.

Deka, Ranjan, and A.K Pachauri. 2006. "Rockfall Velocity Simulation Modelling and Potentials of Geographic Information sciences(GIS) in Its Evaluation." *Emerald Group* 16: 771–784.

Descoeudres, F., 1997. Aspects géomécaniques des instabilités de falaises rocheuses et des chutes de blocs. *Soc. Suisse Mécan. Sols Roch.* 135: 3-11.

Dorren, L. K. A., and G.B.M Heuvelink. 2004. "Effect of Support Size on the Accuracy of a Distributed Rockfall Model." *International Journal ofGeographical Information System* 18 (6) (September): 595–609. doi:10.1080/13658810410001703804.

Dorren, L. K.A. 2003. "A Review of Rockfall Mechanics and Modelling Approaches." *Progress in Physical Geography* 27 (1): 69.

Dorren, Luuk K. A., Bernhard Maier, Uif S. Putters, and Arie C. Seijmonsbergen. 2004. "Combining Field and Modelling Techniques to Assess Rockfall Dynamics on a Protection Forest Hillslope in the European Alps." *Geomorphology* 57 (3-4) (February 10): 151–167. doi:doi: 10.1016/S0169-555X(03)00100-4.

Dorren, Luuk, Frederic Berger, Celine Hir, Eric Mermin, and Pascal Tardif. 2005. "Mechanisms, Effect and Management Implications of Rockfall in Forests." *Forest Ecology and Management* 215 (1-3) (August): 183–195.

Dorren, L. K. A., F. Berger, and U. S. Putters. 2006. "Real-size Experiments and 3-D Simulation of Rockfall on Forested and Non-forested Slopes." *Nat. Hazards Earth Syst. Sci.* 6 (1) (February 15): 145–153. doi:10.5194/nhess-6-145-2006.

Dorren L.K.A., 2011. Rockyfor3D (v4.1) revealed – *Transparent description of the complete 3D rockfall model*. ecorisQ paper (www.ecorisq.org): 30 p.

Erismann, T.H., and G. Abele. 2001. *Dynamics of Rockslides and Rockfalls*. Springer Verlag.

Gupta, R.P. 2004. "GIS-based Rockfall Modelling." *Himalayan Geology* 25 (1).

Le Hir, C., F. Berger, L. K.A Dorren, and C. Quetel. 2004. "Forest: a Natural Means of Protection Against Rockfall, but How to Reach Sustainable Mitigation." In *Proceedings of the International Symposium Interpraevent*, 59–69.

Habib, P., 1977, *Note sur le rebondissement des blocs rocheux*. In: Proc. Meet. on Rockfall Dynamics and Protective Works. Bergamo, Italy. ISMES Publ. 90: pp. 123-125.

Hoesle, B. 2001. "Rock Fall Problems and Its Protection." *Course Script, Department of Civil and Structural Engineering, The Hong Kong Polytechnic University*.

Iswar Chandra Das. 2011. "*Spatial Statistical Modelling for Assessing Landslide Hazard and Vulnerability*". *Enschede, Netherlands*: ITC, University of Twente.

Jaganath Nayak. 2010. "*Landslide Risk Assessment Along a Major Road Corridoor, Based on Historical Landslide Inventory and Traffice Analysis*." ITC, University of Twente.

Joshi, M., and PD Pant. 1990. "Causes and Remedial Measures for Rockfalls and Landslides on Naina Peak, Nainital, Kumaun Himalaya, UP, India." *Mountain Research and Development* 10 (4): 343–346.

Kirby, M.J, and Ian Statham. 1975. "Surface Stone Movement and Scree Formation." *The Journal of Geology* 83 (3): 349–362.

Loye, A, M Jaboyedoff, and A Pedrazzini. 2009. "Identification of Potential Rockfall Source Areas at a Regional Scale Using a DEM-based Geomorphometric Analysis." *Natural Hazards and Earth System Sciences* 9 (5) (October): 1643–1653.

Motta, Renzo, and Jean-Claude Haudemand. 2000. "Protective Forests and Silvicultural Stability: An Example of Planning in the Aosta Valley." *Mountain Research and Development* 20 (2) (May 1): 180–187.

Omura, H. and Marumo, Y.1988. An experimental study of the fense effects of protection forest on the interception of shallow mass movement. *Mitteilungen der Forstlichen Bundesversuchasanstalt Mariabrunn / Wien* 159, 139-147

Pichler, B., Hellmich, Ch. and Mang, H.A., 2005. Impact of rocks onto gravel - design and evaluation of experiments. *Int. J. Impact Eng.* 31: 559–578.

Pfeiffer T.J. and Bowen T.D., 1989. Computer simulation of rockfalls. *Bull. Ass. Eng. Geol. XXVI*: 135-146.

Rautela, Piyoosh. 2005. "Increasing Vulnerability of the Himalayan Urban Centers." http://dmmc.uk.gov.in/files/Documents/urban%20centers.pdf.

Rouiller, J. D., Jaboyedoff, M., Marro, C., Philippossian, F., and Mamin, M.: Pentes instables dans le Pennique valaisan. Matterock: une m´ethodologie d'auscultation des falaises et de d´etection des ´eboulements majeurs potentiels, *Rapport final du PNR31, VDF Hochschulverlag* AG, ETH Z¨urich, Switzerland, 1998.

Schonenberger, W, and P Brang. 2004. "Silviculture in Mountain Forests." *Encyclopedia of Forest Sciences*. Amsterdam: Elsevier.

Shroder Jr, J.F., and M.P. Bishop. 1998. "Mass Movement in the Himalaya: New Insights and Research Directions." *Geomorphology* 26 (1-3): 13–35.

Spang, R.M., 1988. *Empirical and mathematical approaches to rockfall protection and their practical applications*. In: Proc. 5th Int. Symp. Landslides, Lausanne: pp. 1237-1243.

Strahler, A. N, 1950. Equilibrium theory of erosional slopes approached by frequency distribution analysis, *Am. J. Sci.*, 248, 673–696, 800–814.

Varnes, D.J. 1978. "Slope Movement Types and Processes." *Transportation Research Board Special Report* (176)

Wu, S.S., 1984, Rockfall evaluation by computer simulation. Transportation Research Record, *Transp. Res. Board*, Washington, DC, Nr. 1031: pp. 1-5.

Zinggeler, A., 1990. *Steinschlagsimulation in Gebirgswäldern – Modellierung der relevanten Teilprozesse*, MSc. Thesis Univ. Bern, Geog. Inst.: 116 p.