Precipitation Intensity-Duration Based Threshold Modelling and Landslide Impact Assessment in Alaknanada Valley

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DISCLAIMER

This work has been carried out in partial fulfilment of Masters in Technology program in Remote Sensing and Geographic Information System at Indian Institute of Remote Sensing, Dehradun, India. The author is solely responsible for the contents of the thesis.

Date: 16 June, 2015 **Shobhana Lakhera**

Certificate

This is to certify that the project entitled "**Precipitation Intensity-Duration based Threshold Modelling and Landslide Impact Assessment in Alaknanda Valley**" is a bona fide record of work carried out by **Ms. Shobhana Lakhera**. The report has been submitted in partial fulfilment of requirement for the award of Master of Technology in Remote Sensing and GIS in Natural Resource Management with specialization in Geosciences, conducted at Indian Institute of Remote Sensing, Dehradun, during 21 Aug 2014 to 14 Aug 2015. The work has been carried out under the supervision of **Dr.P.K.Champati Ray**, Head, G&DMS and Dr. Shoval Lal Chattoraj, Scientist/Engineer 'SD' Geosciences and Geohazards Department.

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ABSTRACT

The Alaknanda valley in Garhwal Himalaya region is prone to geological hazards majorly landslides due to its tectonic dynamism, topographic characteristics and increasing anthropogenic activities in the area, causing loss of life and property. The entire area receives heavy rainfall every year during July and September, as a result several incidences of landslides and related secondary hazards like flash floods are reported from various parts of the Alaknanda valley, mainly along the NH-58 national highway. It is therefore important to predict and study landslides in this area.

Landslide activity in the Alaknanda valley is pronounced majorly in the monsoon season; therefore it is imperative to study the effect of rainfall on landslide initiation in the study area and determine the susceptibility of the area to landslide activity. Thus the present study aims to generate an early warning system for landslide by deducing intensity duration based rainfall thresholds.

The three-hourly rainfall intensity and duration values from the tropical rainfall measuring mission and landslide event records from Border road organization (BRO), have been used for determining the intensity duration(ID) based threshold for rainfall triggered landslide events . The validation of the I-D equation is carried out using the monsoon dates from 1st June to 1st October for the years 2013 and 2014 and an accuracy of prediction of 86.15% for the landslide events and 92.59% for the non-landslide events has been achieved. The susceptibility zonation has been performed for the study area to delineate high susceptible areas for landslides and demarcate between very high, high moderate and low and very low risk areas. A resultant Landslide Susceptibility Map is prepared depicting the above mentioned demarcations and is validated based on the 244 landslide locations acquired from Google Earth and it is observed that 84.4% of the landslide point location fall under high and very high susceptible areas, whereas 15.6% of the landslide points fall under moderate and low susceptible areas. Also it is noted that the high and very high susceptible areas are profoundly along the drainage corridors and the higher slope areas. The Mass wasting map prepared as an outcome of automated change detection for mapping landslide demarcates high change areas as the mass wasting zones which like the susceptibility map are located along the drainage and the higher slope zones, thus the analysis concludes that major areas of impact and susceptibility are along the drainage course and the higher slopes. Also Modeling of major landslide has been attempted using the rapid movement mass flow (RAMMS) software to model major debris flow in the study area to determine and predict run out areas so that preventionary measures can be accounted for.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

1.1 Background

Landslides are defined as the movement of a mass of rock, debris or earth down the slope under the action of gravitational acceleration force. landslides hence encompass mass movements of all types namely-falling, sliding and flowing and these oftenly occur in combination with cloudburst, heavy rainfall, volcanic eruption, earthquakes, and floods majorly in high altitude regions. The factors controlling slope instability encompass the following factors that involve geology, geomorphology and hydrology along with intricate tectonics, geodynamics and meteo-climatic factors in an area. Increased urbanization, accompanied by expansion of roads also creates an increasing pressure on the landscape, and also leads to higher degrees of vulnerability to the occurence of landslide activity in the region. Also the devastation of forest land and the vegetation land which bind the topmost soil at an increasing pace and the conversion of forest land into agricultural and horticultural holdings also adds to the increasing landslide susceptibility of the terrain.

The Alaknanda river basin in, Uttarakhand is characterised by deep gorges and rugged mountains and has high frequency of landslides encountred majorly during the monsoon season. The part of the National Highway 58 taken up for the study runs for 128km, aligned alongside the river passageway Alaknanda from Karanpryag to Mana village. The highway has been made by excavations in the fluvio-glacial material and talus deposits on the slopes of valleys . All these towns are generally established alongside the road passage. The expansion of this road together with rapid urbanization has rendered these unstable hill slopes, apparently more susceptible to slope failures.

1.2 Problem Statement

Every year during intense rainfall periods, several incidences of landslides and related casualties are reported from different parts of the Rishikesh-Badrinath National highway 58, in the state of Uttarakhand, India. The upper part of Alaknanda valley is very prone to landslides and landslide activity is common along this road stretch. This road is the only motorable route connecting Badrinath, an important Hindu pilgrimage center and other hill cities to the rest of the nation. Slope failures lead to disruption of traffic hence leaving the pilgrims, tourists and inhabitants grounded for several hours. Destruction of the highway has deeper impacts as many towns, villages and hamlets are often marooned from the entire of the country. Also Landslides and the involved secondary hazards such as landslide dams and subsequent flash floods often turn into major disasters and cause destruction in the downstream areas. Given these disastrous effects it is therefore imperative to access and predict landslides in this region.

Remote sensing techniques have been widely used in landslide research and spectral and spatial imagery have been employed. This research includes photo-interpretation and inventory of large landslides, automatic detection and mapping of vulnerable zones by textural and spectral analysis and susceptibility mapping for landslides. The textural and spectral analyses are usually a good approaches to landslide delineation, and hence discrimination between unstable and stable zones i.e. detection of vulnerable zones. Traditionally landslide mapping has relied on visual interpretation of aerial photographs, but with advances in technology, now high resolution images are used, pixel based automated techniques are now greatly used in mapping of landslides and their vulnerable zones. The mapping of landslide prone areas is also very important in hazard prone areas, hence landslide hazard zonation becomes an essential aid for the crucial areas. Also the weights relatively given to different layers of map here come into play and weights are to be allotted based upon the importance and influence of the layers and their impact in landslide initiation in the study area.

Thus the present study aims to understand precipitation as a triggering mechanism and establish intensity duration based precipitation thresholds for landslide initiation, and also monitoring and identifying landslide vulnerable zones and physical process based modeling for landslide hazard mitigation and future run-out zones identification.

1.3 Objectives

1. To study the influence of rainfall on landslide initiation and establish Intensity-duration (hourly) based rainfall thresholds.
2. To apply automated change detection technique for monitoring landslide activity.
3. To study impact of 2013 disaster event in Alaknanda Valley.
4. Simulate major landslide events by using physical process based model.

1.4 Research Questions

1. What is the precipitation threshold based on intensity for landslides in using TRMM data?
2. How far can automated change detection technique help in the monitoring of Landslides?
3. What are the impacts of 2013 disaster in Alaknanda valley?
4. How to simulate landslide and validate results obtained by physical process based model?

2. LITERATURE REVIEW

2.1 Landslides and Slope Instability

The term "landslide" describes a wide variety of processes that result in the downward and outward movement of slope-forming materials which comprise rock, soil, artificial fill, or any combination of all of these. And these materials may move by the following methods, I.e. falling movement, sliding, toppling, spreading, or flowing movement.

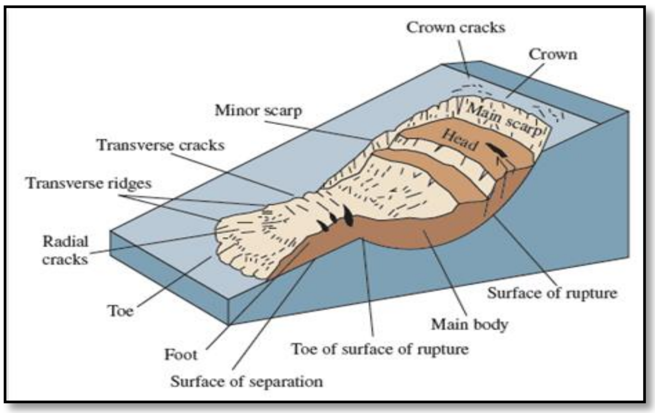

Figure 1: Landslide Terminology

2.1.1 Classification of Landslides

The various types of landslides can be differentiated by the kinds of material involved and the mode of movement.

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

Figure 2: Types of Landslides (Varnes, 1978)

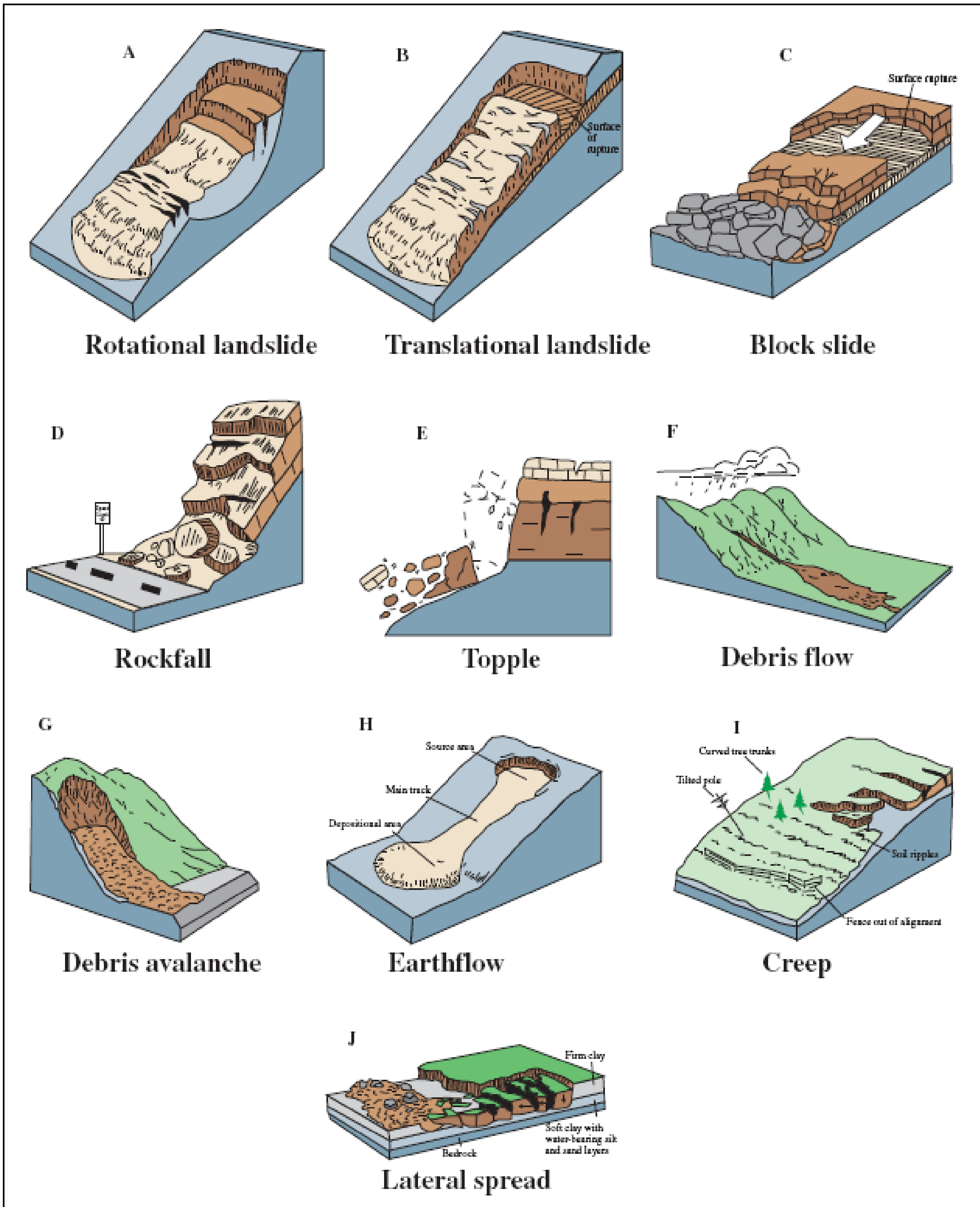

Figure 3: type of landslides (http://landslides.usgs.gov/html_files/nlic/nlicmisc.html/)

2.1.2 Causal Factors

The force governing the dynamic landscape processes is the constant pull of gravity which makes all hill slopes susceptible to failure. Upon failure, the earth material moves down slope until slope stability is re-established. Besides gravity, geology, geomorphology, hydrology and anthropogenic factors contribute largely towards destabilization of slopes.

The USGS landslide group classifies the causal factors as follows:

1. Geological causes

a. Weak or sensitive materials

b. Weathered materials

c. Sheared, jointed, or fissured materials

d. Adversely oriented discontinuity (bedding, schistosity, fault and unconformity.)

e. Contrast in permeability and/or stiffness of materials

2. Morphological causes

a. Tectonic or volcanic uplift

b. Glacial rebound

c. Fluvial, wave, or glacial erosion of slope toe or lateral margins

d. Subterranean erosion (solution, piping)

e. Deposition loading slope or its crest

f. Vegetation removal (by fire, drought)

g. Thawing

h. Freeze-and-thaw weathering

i. Shrink-and-swell weathering

3. Human causes

a. Excavation of slope or its toe

b. Loading of slope or its crest

c. Drawdown (of reservoirs)

d. Deforestation

e. Irrigation

f. Mining

g. Artificial vibration

h. Water leakage from utilities

2.1.3 Triggering Factors

Triggering factors lead to a sudden instability in a slope and usually precede the failure. These include heavy rainfall, earthquakes, volcanism and cloudburst. Even man-modifications of natural slopes such as road excavations or land use, land cover changes can make a slope liable to fail or even trigger a slide immediately.

2.2 Landslide-Triggering Rainfall Thresholds

Threshold defines the minimum or maximum (critical) level of some quantity needed for a process to take place. Thus rainfall threshold can be defined as the lowest level of rainfall above which one or more landslide can be triggered.

Hence, two types of landslide-triggering rainfall thresholds can be defined:

• Empirical thresholds, based on historic analysis of relationship between rainfall and landslide occurrence. The approach identifies the rainfall value above which slope failure takes place.

• Physical thresholds, which rest on numeric models and take into account the relationship between rainfalls, pore pressure and slope stability by coupling hydrologic and stability models (Crosta, 1998).

Physical thresholds are not widely developed and, generally, they require detailed knowledge of the boundary conditions, which are seldom available outside specially equipped test fields (rain gauges, piezometers, tensiometers). Attempts at a regional scale have been proposed by using distributed models (Aleotti et al., 2003). On the contrary, there are a fair number of empirical thresholds and different graphs have been used to represent them, depending upon combinations of the most commonly used rainfall parameters: antecedent rainfall, duration, intensity, cumulative rainfall. In the first suggested elaboration, the triggering thresholds are simply defined either by the critical cumulative rainfall or by the rainfall intensity. The most commonly used thresholds are those defining the intensity–duration (Caine, 1980). The intensity–duration approach can be further refined by normalizing the intensity value with the mean annual rainfall (MAP), emphasizing the regionalization of the thresholds, thus the calculation takes into account the climatic regimes of the study area.

2.2.1 Intensity Duration Based Rainfall Thresholds

Rainfall triggered landslides are very comm0on in mountainous regions throughout the world. Due to growth in human population and advancement in anthropogenic activities the landslide susceptible areas are increased. A common goal of landslide research is to improve predictions of landslides events. Critical thresholds are used to define metrological, geotechnical or hydrological conditions which, whenever exceeded, are possibily to produce landslides or debris flows (Caine 1980).So, intensity and duration based rainfall thresholds (ID), thresholds can be defined empirically using historical data(Aleotti 2004), theoretically using physically based models, or some combination of physical and empirical thresholds as by (Crozier 1999). But the problem with physical threshold which as discussed above is that they rquire detailed metrological, hydrological and geotechnical data for accurate model calibration and prediction, and all this data is very difficult to obtain over large area. Therefore, regional and global predictions of the occurrence of landslide and debris floe events are usually made using empirical threshold derived from more easily obtained data on rainfall and the presence or absence of landslide and debris flows during a given storm.

Empirical intensity duration based thresholds are generally based on power laws and represented by the same in the form of I=aD^b, where I is the rainfall intensity in mm/hour, d is the duration in hours, and a and b are empirically derived parameters. The threshold approach for prediction of debris flows and slides using power law equation is based mainly on two basic assumptions,

1. A non-linear increase in probability of landslide or debris flow with increase in the rainfall intensity, which is depicted by the actual value of threshold for slide or flow initiation. Below the threshold value there is a lesser probability of slide or debris flow initiation and at the

threshold there is a rapid non-linear increase in the probability of initiation. Intensity value the coefficient a and b define the location of critical intensity value.

2. The second assumption states that, as the rainfall increases, there is a decrease in the intensity of the rainfall that is required to trigger landslide. In the power law equation, the exponent b defines the rate at which critical intensity decreases with increasing rainfall duration.

The, intensity duration thresholds for landslide prediction must essentially meet the following criteria (Dennis, Jason, 2012).

1. The threshold rainfall intensities must be a representative of the rainfall intensities that contribute to the initiation of landslide or debris flows.

2. The landslide events should occur the time the ID thresholds have been exceeded.

3. The number of instances where events occur below the threshold value must be minimized.

4. The number of rainfall events that lead to landslide events but did not exceed.

Hence subjectively rainfall thresholds are generally defined by lower limit of rainfall intensities above which a landslide event would be triggered. This approach is referred to as lower limit method of threshold definition. This represents a most conservative rainfall conditions for debris flow initiation, where rainfall intensities that occur above the threshold value do not result in the initiation of landslides or debris flows. The second approach defines rainfall thresholds at upper limit of rainfall intensities of storms that did not produce a landslide event (Larson and Simon 1993). This approach hence is referred to as upper limit method of threshold definition. These represent a less conservative estimation of the landslide triggering conditions.

2.2.2 Physical Significance of Rainfall Thresholds

Although triggering of shallow landslides by intense rainfall has been widely observed, the processes by which this occurs can be complex. Rainfall infiltration under unsaturated conditions may reduce soil moisture suction; however, this process is not generally viewed as capable of triggering debris flows. Instead, most studies indicate that debris flows result from development of positive pore water pressures that accompany saturation, particularly near decreases in material permeability (Iverson et al. 1997). Measurement of positive pore pressures during periods of intense rainfall and associated triggering of shallow landslides supports the premise that locally elevated pore pressures are responsible for triggering debris flows (Wilson, 1995).

Thresholding is done by drawing lower bound lines on the plots representing landslide triggering rainfall events. Based on the extent the threshold can be global, regional or local. (Mathew, Babu 2013). Not much attempts have been made to determine thresholds for landslides in the Himalaya. Intensity duration based thresholds were established by Dahal and Hasegawa (2008) using long term records of rainfall and landslide data. The relation presented by them is I=73.9D^0.79 as the lower boundary of the field defined by landslide triggering 193 rainfall-induced landslides. Kuthari (2007) studied the rainfall induced landslide events along the NH-58 national highway from Rishikesh to Mana and derived lower bound thresholds relating 3 and 15 day total antecedent rainfall values prior to the landslide events. The threshold equations were derived from single and multiple landslide events on the same day. The other studies have related individual large or multiple landslides associated with abnormal rainfalls and then derived the thresholds. Gupta and Bisht(2004) described the Vurunavat landslide of Uttrakhand Himalaya with its reference to the monsoon rainfall. Subrat Sharma(2012) correletated the extreme rainfall events of 18th and 19th September 2010 in Uttrakhand Himalaya, with the slope failure occurring immediately after the initiation. Hence intensity duration based thresholds based on landslide events are necessary to establish reliable rainfall thresholds for rainfall-induced landslides in the Himalayas.

2.3 Landslide Hazard Zonation and Susceptibility Mapping

Landslide hazard is defined as the probability for a landslide within a given area and within a given period of time (Varnes, 1984). Thus the spatial prediction of landslide is termed as landslide susceptibility, which is a function of landslide and landslide related internal factors. The aim is to identify places of landslide occurrence over a region on the basis of a set of internal causative factors. This is specifically known as landslide susceptibility zonation (LSZ), which can formally be defined as the division of land surface into near-homogeneous zones and then ranking these according to the degrees of actual or potential hazard due to landslides.

The LHZ map divides the landslide prone hilly terrain into different zones according to the relative degree of susceptibility to land-slides. This requires the Identification of those regions that are, or that could be affected by landslides, and the assessment of the probability of such landslides occurring within a specific period of time. The methodology to develop landslide hazard map depends upon several factors like the type of terrain, factors to be considered, availability f data on geology, soil, slope, rainfall, seismicity etc. For the simplicity, we can discuss available methods in five groups.

Classification of landslide hazard methodologies is subjective. These methods are broadly classified as quantitative and qualitative.

2.3.1 Qualitative Methods

Qualitative methods of landslide hazard assessment are used with expert knowledge and expert experiences. This is the easiest process of landslide hazard zonation and can be used directly in the field by geomorphologists or geologist. This method was mostly used during 1970 to 1980 (Aleotti et.al, 1999). Landslide hazard zonation is based on this geological and geomorphologic attributes are more popular particularly for regional scale. These methods can be widely classified into two types: Field analysis and Use index maps or parameter maps with or without weights.

Field analysis

In field a direct method known as geomorphological mapping of landslide hazard zonation is used that depend on efficiency of investigator to estimate the actual and potential failure of slope based on his earlier experience. This method depends on how much researcher understands and knows geomorphological processes acting upon the area. Results are highly varying person to person and instability factors are weighted and ranked according to their expected or assumed importance in causing slope failure.

Use of index or parameter maps

Analytical Hierarchy Process (AHP) was developed by Saaty in 1980. It is useful for the formalization of our non-rational understanding of a complex or composite problem using a hierarchical structure. AHP method was used to determine regions and areas which are susceptible to landslides, here it assigns values to every factor causative of landslide susceptible areas that have been observed in aerial photographs and evaluate the total susceptibility of landslide using that score provided to each factor leading to landslide activity. So, AHP method uses the subjective judgment and the experience of researcher into a layer structure, and expresses the process in a quantitative manner. Hence, the landslide susceptibility here means the possibility of another landslide in the region where landslides have been occurred in the earlier in the past. AHP method uses initial subjectivity.

2.3.2Quantitative Methods

This method has been developed to rectify high level of subjectivity in connection with better judgement evaluation of experts. Thus the evaluation encompasses the determination of various combination of variables and these variables was main reason of earlier instability after that these methods are performed for stable slope and region where similar condition exist

Statically Methods

The statically methods are based on relationships that have been observed between every factors that have contributed to present and past landslide distribution. All possible causative terrain parameters are weighted and integrated using GIS for landslide susceptibility analysis. The reliability of functional method is depends on quantity and reliability of the collected data. Bivariate, multivariate statistic and favorability functions are used to analyze the parameters of instability (Carrare et al., 1991).

Multivariate statistical model were developed for landslide hazard zonation by Carrara et al. in the year 1991. Here, in their application, the morphometric units are reclassified into the classes of landslide hazard. The method is hence based upon the determination of the absence or presence of landslide in any area. And the resulting matrix is analyzed by using multiple regression methods. Thus a statistical model of slope instability in hazard is assessed through correlation of past landslides with several influential factors. Although multivariate techniques can be applied to different scales landslide zonation, their use becomes quite bounded at the regional scale, where exact input map of landslide occurrences may not be available and most of the causative factors cannot be collected with satisfactory level of accuracy. Also at macro scales, different factors will have to be used such as the depth of ground water in the region, soil sequences present and their thickness. These data are very difficult to found even for relatively small areas. Therefore, the medium scale is believed most appropriate for multivariate analysis.

In Bivariate Statistical models, the influence of individual factors or combination of factors that are related to slope failure is evaluated. Here in every individual class, the weight or the contribution of a causative factor for the landslide hazard is determined based upon the landslide density.

GIS method for bivariate analysis usually encompasses:

(1) The division of each parameter map into no of relevant classes.

(2) The determination of landslide density and weighting the value of each parameter map.

(3) The overlaying of the landslide map with each parameter map.

(4) Determining of landslide density and weighting the value of each parameter class.

(5) The assignment of weighting values to the various parameters maps.

(6) The final overlay mapping using a decision rule and determination of susceptibility threshold values.

 (7) The classification of the resulting score in a landslide classes.

The main drawback of bivariate statistical method is the independency between different parameter maps with respect to probability to landslide occurrence, due the assumption of conditional independency. However the assumption is generally invalid. This problem can be solved by developing the combined dependent maps from the data and then preparing a new parameter map (Van Westen et al.,1997).

2.4 Automated Change Detection for Landslide Mapping

Change detection procedures intend to find and interpret the alterations of objects or phenomenon between the different acquiring times. When using multitemporal landslide data , the value of an image pixel or object at a time can be compared with the value of the corresponding image pixel or object at another time in order to determine the degree of change. Many different procedures have been developed depending on the spatial, the spectral and the temporal resolution of the available imagery and c computer capacities in regard to digital image processing. At the same time the variety of change detection applications has increased whereas the first change detection studies particularly focused on large scale and possibly long term changes of land use and land cover i.e vegetation, forest, agriculture and urban areas. but now the techniques for change detection have broadened the influence area and have found increased applications in landslide mapping and inventory preparations.

Landslide inventories, are prerequisite for landslide hazard and risk assessment, so far for many parts of the world such multitemporal landslide inventories are largely missing because the preparation relies mainly on the time consuming and resource intensive conventional methods which are rooted on visual interpretation of optical data aided by comprehensive field surveys. Against this the long time archives' of satellite remote sensing data and high resolution satellite imageries open up new opportunities for analyses of landslide occurrence at a regional scale. Thus change detection techniques are now been employed for mapping and zonation of landslides, several approaches based on automated multisensory pre-processing and multi-temporal change detection methods. Change detection requires precise spatial alignment of the whole database which is a pre-requisite. An approach for landslide mapping using change detection based on analysis of temporal NDVI trajectories was developed for mapping landslide (Behling,2014). The NDVI trajectories are obtained for every pixel across the analyzed time span. NDVI trajectories represent specific temporal footprints of vegetation differences. These enable for automatic identification of landslide events due to landslide specific footprints represented by short term destruction of vegetation cover as well as longer term of revegetation rates as the affects of landslides related disturbance and dislocation of soil in combination with DEM derivatives example slope, stream order etc. thus enabling automated object based identification of landslides of different sizes shapes and is suitable for mapping spatio- temporal landslide activities under varying natural conditions.

Other change detection approach involves object oriented approach (OAA). OAA, which is based on image segmentation and subsequent classification of derived image primitives, represent a more advantageous approach for analyzing high resolution data, because image pixels can be meaningfully grouped into networked homogenous objects and noise can be consequently reduced. Moreover, OOA offers a potentially automated approach for landslide mapping, with a consideration of spectral, morphological and contextual; landslide features supported by expert knowledge. Thus allowing a cognitive approach that is comparable to visual image analysis. So far few studies have used OOA for landslide mapping. Although automated detection of landslides using low resolution imagery have been carried out by Barlow et.al. Using landset(ETM+) images. The methodology was further improved by the use of higher resolution SPOT-5 data as well as an inclusion of more robust geomorphic variables. Also Martha et all integrated spectral spatial and mormhometric features to successfully recognize and classify five different types of landslides in different terrain in the high Himalayas. These studies show the increasing utility and potential of OOA in detecting and mapping landslides.

2.5 RAMMS (Rapid Mass Movements)

Debris flows are one of the types of mass movements that cause significant damage to properties and loss of lives, as they often occur in those parts of mountainous environments that are most utilized by human activities, e.x. alluvial fans and floodplains. Moreover expansion of the infrastructure for tourism and winter recreational purposes has further increased the risk of people and property being affected by the debris flows. Therefore estimation of the debris flow run-out and related intensities like height and velocity is important to link the hazard with the vulnerability and related losses of elements at risk to debris flows.

A considerable number of approaches have been developed to predict the run-out of debris flows, which can be generally divided into three different groups: empirical statistical methods, analytical methods and numerical methods.

The numerical methods have the strong advantage of being able to calculate the movement of the flow over irregular topographic terrains. Furthermore, they can compute intensity related parameters like the flow depth and impact pressure at every point in the flow path which can be coupled to vulnerability functions for quantitative risk assessment .As part of the numerical methods, dynamic continuum models use fluid mechanics applying conservation equations of mass, momentum and energy. These equations which describe the debris flow dynamic motion are further integrated with respect to the flow depth to create an approach that is called depth averaging approach. Here the dynamic models can either be 1-D models that move the flow in only one spatial dimension as a cross section of a single pre-defined width or 2-D models that move the flow in two dimensions, considering the topography in the plan surface and cross-section. Rheology is used in dynamic models to further describe the frictional behavior of the debris flow material. What is essential in dynamic continuum modeling is the choice of an accurate rheology (Rickenmann, 2005). The most common rheologies used in dynamic models are: Frictional resistance, the frictional-turbulent "Voellmy" resistance (Voellmy, 1955);

The Voellmy equation roted model has produced good results in debris flow analysis and is one of the most widely used rheologies to simulate debris flows.

RAMMS (Rapid Mass Movements) is a dynamic numerical modeling software package developed by the Swiss Federal Institute for Snow Avalanche Research (WSL/SLF) originally to model snow. However, it has also been applied to model other types of mass movements like rock avalanches and debris. The 2-D model is capable of predicting the run-out path, velocities, flow heights and impact pressures in a two and three dimensional environment. The flow model is a generalization of the quasi one-dimensional model. RAMMS uses the Voellmy-Salm fluid flow continuum model on the Voellmy-fluid flow law (Voellmy, 1955) and describes the debris flow as a hydraulic-based depth-average continuum model. The flow resistance is divided into a dry-Coulomb friction (μ) and a viscous resistance turbulent friction.

$$\boxed{S = \mu\rho H g\cos(\varphi) + \rho g U^2/\xi} \qquad 2.1$$

Here,

β= flow density

g= gravitational acceleration

μ=dry friction

Ø=slope angle

€=velocity squared drag coefficient (viscous turbulent friction)

H-flow height

U=flow velocity.

This model has found wide application in modeling of debris flows all over the world. One reason Vollemy is useful in debris flow modeling is that it only requires two parameters to calibrate. The turbulent term dominates the frictional behavior when the flow is moving rapidly and the dry friction term is useful when the flow is moving slowly, allowing the model to be approximately calibrated to observations of flow velocity and the stopping location of flow front.

The RAMMS environment uses three dimensions: x and y are the directions of the mass movement flowing down the topographic surface and the elevation is given by z(x,y), which is perpendicular to the profile. The gravitational acceleration vector in the three directions is g = (gx, gy, gz) and the time component is defined as t. The flow is moved in an unsteady and non-uniform motion and is characterized by two main flow parameters, that incomporates the height of flow H(x, y, t) (m) and the mean velocity U(x, y, t) (m/s). The initial height is determined by the user when defining the source area of the debris flow as a polygon. The Voellmy-Salm model uses the mass balance equation:

$$\partial_t H + \partial_x (\mathrm{HU}_x) + \partial_y \ \mathrm{HU}_y\big) = Q(xyt), \qquad 2.2$$

Where Ux and Uy are the velocities in the x and y directions. Q(x, y, t) in meter per second(m/s) is the mass production source term, also called the entrainment rate (Q >0) or deposition rate (Q<0) (Christen et al., 2010). The depth-averaged momentum balance equations in the x and y directions are respectively given by:

$$\begin{aligned}&\partial_t (\mathrm{HU}_x) + \partial_x \left(c_x \mathrm{HU}_x^2 + g_z k_{a/p} \frac{H^2}{2} \right.\\ &+\partial_y \ \mathrm{HU}_x U_y\big) = S_{g_x} - S_{f_x}\end{aligned} \qquad 2.3$$

$$\begin{aligned}&\partial_t \ \mathrm{HU}_y\big) + \partial_y \left(c_y \mathrm{HU}_y^2 + g_z k_{a/p} \frac{H^2}{2} \right.\\ &+\partial_x \ \mathrm{HU}_x U_y\big) = S_{g_y} - S_{f_y}\end{aligned} \qquad 2.4$$

Where, cx and cy are profile shape factors that are determined by the DEM and ka/p is the earth pressure coefficient that was set to 1 to model hydrostatically the flow. This was also the result found in previous studies (Bartelt et al., 1999). Equations (2) and (3) include the gravitational accelerations given in the x and y directions that are respectively given by:

$$S_{gx} = g_x H$$

$$S_{gy} = g_y H \qquad 2.6$$

Equations (2) and (3) further contain on the right-hand side the driving frictions also given the x and y directions and are respectively given by:

$$S_{f_x} = n_{U_x} \left[\mu g_z H + \frac{g||U||^2}{\xi} \right] \quad 2.7$$

$$S_{f_y} = n_{U_y} \left[\mu g_z H + \frac{g||U||^2}{\xi} \right], \quad 2.8$$

Where, nUx and nUy are velocity directional unit vectors in the respective x and y direction. Hence, the total basal friction in the Voellmy-Salm model is split into a velocity independent dry-Coulomb friction coefficient μ and a velocity dependent turbulent friction coefficient ξ(m/s2). For the sake of simplicity, μ is named the friction coefficient and ξ the turbulent coefficient.

Here ρ (kgm−3) is the density of the initiated incoming debris flow, τ is the shear stress, and hs (x,y,0) (m) is the initial height of the entrainment layer at position (x,y) and time t =0s. The total height of the entrainment layer in RAMMS can be divided into three separate layers: i {1, 2, 3 } so that hs = 6hi and the density of the each

3. STUDY AREA

The Alaknanda river basin extending from 29° 58’ 11.315’’N to 31° 6’21.183’’ N and 78° 32 31.406’’E to 80° 17’ 26.161’’ E. is studied. It encompasses seven districts Chamoli, mandakini, Badrinath, Nandakini, Pindar, Dhauliganga, Devprayag and Birehiganga. Impact analysis is done for the entire Alaknanda valley. The intensity- duration (ID) threshold analysis is carried out for seven major stations along NH-58 highway between Karanprayag to Lambagarh. The study area is characterized by deep gorges and resilient peaks, characterized by a maximum elevation of 7811m and minimum elevation of 445m with respect to the mean sea level.

Frequent slope failures that are observed during monsoon majorly along NH-58 national passageway. Here, landslide activity are the result of heavy rainfall, intricate tectonic setting with a unique geomorphology of steep slopes and dissected hills.

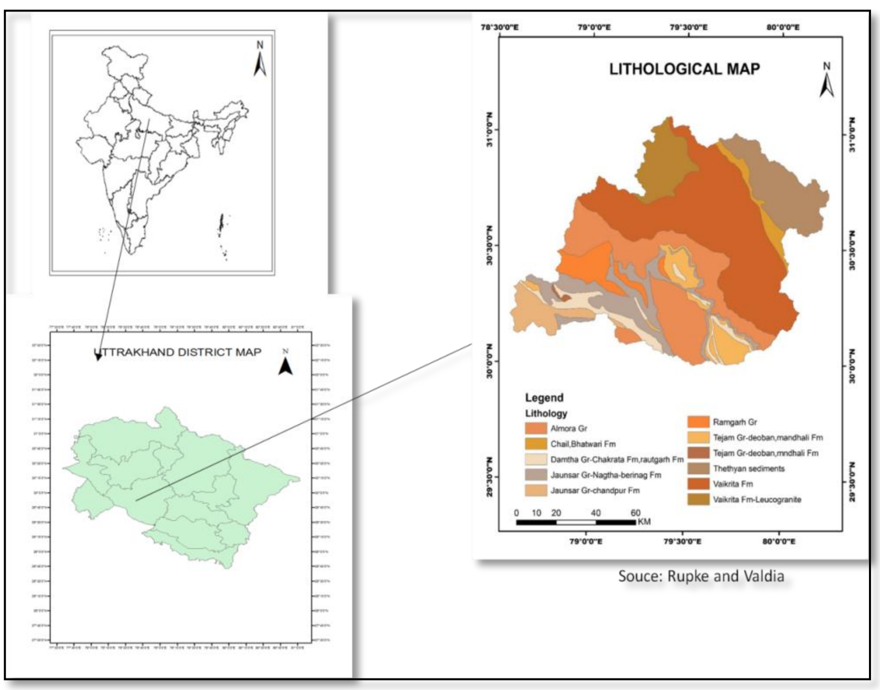

Figure 4: Alaknanda valley

3.1 Geology:

Geologically the Alaknanda valley consists of three major lithostartigraphic units known as the Dhudhatoli Group, the Garhwal Group and the Central Crystalline Group (Sharma 2003). The zone between Devprayag and Koteshwar consists metamorphosed rocks particularly phyllites and quartzites forming the Dhudatoli Group, which is separated by the North Almora Thrust trending in NW-SE direction. The rocks of the Garhwal Group are exposed uptil Vishnuprayag and are mainly quartzites, shales and slates, shists and carbonates occasionally intruded with meta -volcanic. The Garhwal Group is seprated by Main Central Thrust trending in NW-SE direction, and consists of several shear and fracture zones. The Northern zone extending from Vishnuprayag to village Mana along the river Alaknanda and Dhualiganga composed of shists, gneiss rocks and granite rocks of Central Crystalline Group, which rest over the Garhwal Group. It is observed that the thrust zones have a general trend of NW-SE parallel to the Himalayan range and perpendicular to river Alaknanda which flows in NW-SE direction.

3.2 Geomorphology:

The Alaknanda valley is characterized by three major categories of landforms high hills, hill sides or hill slopes and river valleys (Sharma 2003). The high hills are, conical shaped peaks ranging above 1500m.The hill slopes exist between the high hills and the river valleys and consists of talus or scree with thick vegetation cover but become scant due to redundancy of landslides. The river valley formations include incised meanders and well developed river terraces of variable height and below with gentle slope. The majority of landforms observed are of structural, glacio-fluvial and denundational origin. The sharp crested peaks, arêtes and broad u-shaped valleys are characteristic of glacial origin and are the most prominent landforms in the high hill areas. Partly to well develop terraces are the major fluvial landforms observed. Some river terraces of higher elevations ranging between 50-100m above the river level, are indicative that the river Alaknanda has deep cut valleys. Hence the main geomorphic classes identified in the area include highly to moderately dissected hills, talus and scree deposits, river terraces and fluvio-glacial material.

3.3 Drainage:

The river Alaknanda originates from Satopanth Glacier and is a major tributary of river Ganges. It is called Alaknanda after its confluence with river Saraswati and Rishi Ganga. The main tributaries of Alaknada namely Dhauliganga tributary, Nandakini, Pindair and Mandakini tributary all rise from high hill watersheds to contribute their waters to the Alaknanda forming subparallel drainage. Consequently the hill slopes are gullied and dissected. Several streams of Alaknanda like the Patal Ganga contribute their waters to it through underground passages which activate the conditions for landslides.

3.4 Road networks:

The NH-58 highway from Karnprayag to Mana is a 128 Km road stretch transecting the study area. The important townships in this area are Devprayag, Nandprayag, Karanprayag, Chamoli, Pipalkoti, Joshimath town, Lambagarh, Helang, Hanuman Chatti, Badrinath and Kedarnath, which are established alongside the roadway. Also brisk urbanization and expansion of the roadway has lead to increased susceptibility to slope failures, which are often encountered during monsoon causing damage of life and property.

3.5 Soil:

The characteristics of soil in the Alaknanda valley vary at different locations. Soil cover in terraces is generally very thin, cultivated areas with moderate slopes have relatively thicker soil cover and precipitous slope are generally without soil cover. In cliffs the soil exists along the cracks. Fine soil is found abundantly on moderate slopes, while coarse soil is abundant on steep slopes.

3.6 Climate:

The Alaknanda river basin is characterized by monsoon climate with frequent and intense rainstorms ranging between 200 to 1000mm/hour (Joshi 2006). Here the amount of rainfall alters with respect to location from windward and leeward side of high ridges. Almost 50% of annual rainfall is received between monsoon months of June and mid-september (Kuthari 2007)

3.7 Vegetation:

Low to moderate vegetation density is observed in the Alaknanda valley. Most of the slopes in higher altitudes are apparently barren with some shrubs, rhododendrons, mosses, lichens and some windflowers. Terrace farming is common and potatoes, pulses and barely are mainly grown.

3.8 Data Set Used

3.8.1 Rainfall Intensity Data:

- TRMM(Tropical Rainfall Measuring Mission)(3-hourly data), Resolution(0.25 by 0.25km)
- TRMM(daily data), Resolution(0.25 by 0.25km)

3.8.2 Optical Data:

- LISS-IV, resolution(5.6m)
- CARTOSAT1 STEREO PAIR, resolution(1m)

3.8.3 Softwares Data used:

- Arc GIS
- Erdas Imagine
- RAMMS: Rapid Mass Movements

3.8.4 Scientific Intrument used:

- Direct shear testing machine(Rocks Triaxial equipment)

3.8.5 Anscillary Data used:

- Geological map(GSI)
- Seismotectonic map(GSI)(2005)
- Land use land cover map(IGBP)(2005)
- BRO(Border Road Organization) landslide inventory data(2013 And 2014)

4. METHODOLOGY

4.1 Intensity duration based precipitation thresholding

Rainfall is the most common triggering factor for landslides, thus attempts on prediction of rainfall induced slope failures involve establishing the relation of intensity and duration of rainfall events to slope destabilization. (John Mathew, 2013). Hence the concept of rainfall threshold has developed. Severe and protracted rainfall events can cause considerable landslides and a number of intensity duration based thresholds have been recognized. The significance of antecedent rainfall on landslide initiation is also recognized and critical rainfall amount have been determined where sufficient amount of information on rainfall and landslide is present. In Alaknanda valley a large number of landslides are encountered mainly during the monsoon hence the effect of intensity and duration of rainfall on landslide initiation is studied here.

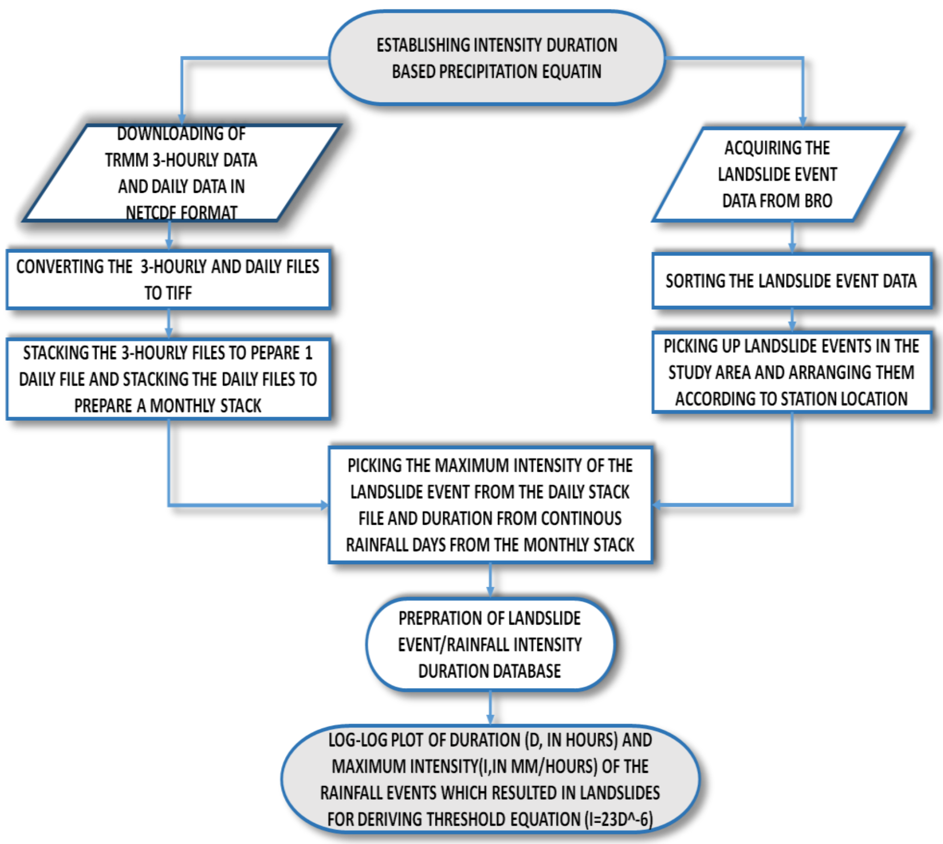

Figure 5: Flow chart of Methodology for I-D Thresholding

4.1.1 Rainfall data

In the present study TRMM 3B42 V.7 data has been used. The rainfall intensity data at three hourly interval and daily interval from 1st January 2013 to 1st October 2014 have been downloaded for the purpose I-D thresholding. The TRMM 3B42 data have been downloaded in netcdf format and then converted to tiff for further evaluation. The maximum intensity values are derived from the 3 hourly files. For each day eight 3 hourly files are stacked to generate a daily file and from this stacked daily file the maximum intensity corresponding to the particular hour is selected. Now the duration is determined from the daily files which are stacked to generate a monthly file and from the monthly stack the duration is calculated as the days of continuous rainfall till the event date.

4.1.2 Landslide Data

The landslide records pertaining to 2013 and 2014 have been gathered from Border Road Organization (BRO). The BRO maintains the NH-58 highway from Rishikesh to Mana and keeps record of any road blockage or damage resulting from slope failure activity in the form of register of landslides, history of landslides and daily road situation report. The landslide database is a combination of all the above stated records. The landslide location is recorded in terms of distance from Ghaziabad. The landslide records were sorted from the BRO database for the year 2013 and 2014 out of which a total of 110 landslide events were recorded. Analysis of the landslide records represented various landslide events on the same date. These make up 35 unique landslide records and have been used for I-D equation calculation.

4.1.3 Database generation

For the generation of the I-D equation a database of maximum intensity on the day of event and the total duration of rainfall till the event day for the 35 unique landslide events was prepared. A graph of maximum intensity to total duration on a log-log plot was prepared to devise the I-D equation for landslide initiation. The validation of the equation is done using a record of maximum intensity to total duration for the entire stretch of monsoon i.e. from June to September for both the years 2013 and 2014. The records were analysed for seven major stations along the NH-58 highway namely Karanprayag, Nandprayag, Chamoli, Pipalkoti, Tangini, Joshimath and Lambagarh.

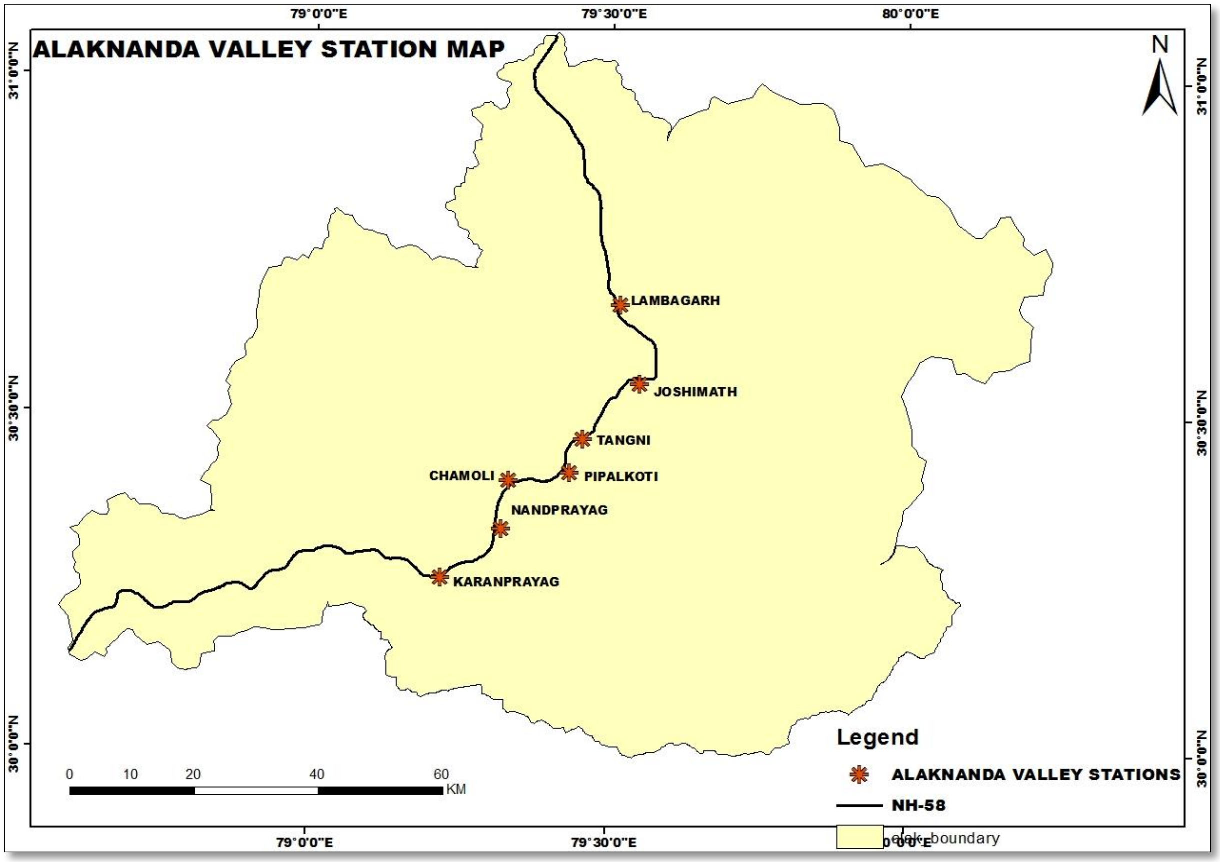

Figure 6: Alaknanda valley station map along NH-58 highway

4.2 Weighted overlay for landslide susceptibility mapping

The Spatial prediction of landslide is termed as landslide susceptibility, which is a function of landslide and landslide related internal factors. The aim is to identify places of landslide occurrence over a region on the basis of a set of internal causative factors. This is specifically known as landslide susceptibility zonation (LSZ), which can formally be defined as the division of land surface into near-homogeneous zones and then ranking these according to the degrees of actual or potential hazard due to landslides (Kunango.D.P., 2009).

Thus the primary objective is to produce the Landslide Susceptibility Map for Alaknanda valley so that appropriate landslide disaster risk reduction strategies can be developed by demarcation of high risk zones. The flow chart of the methodology adopted is given as:

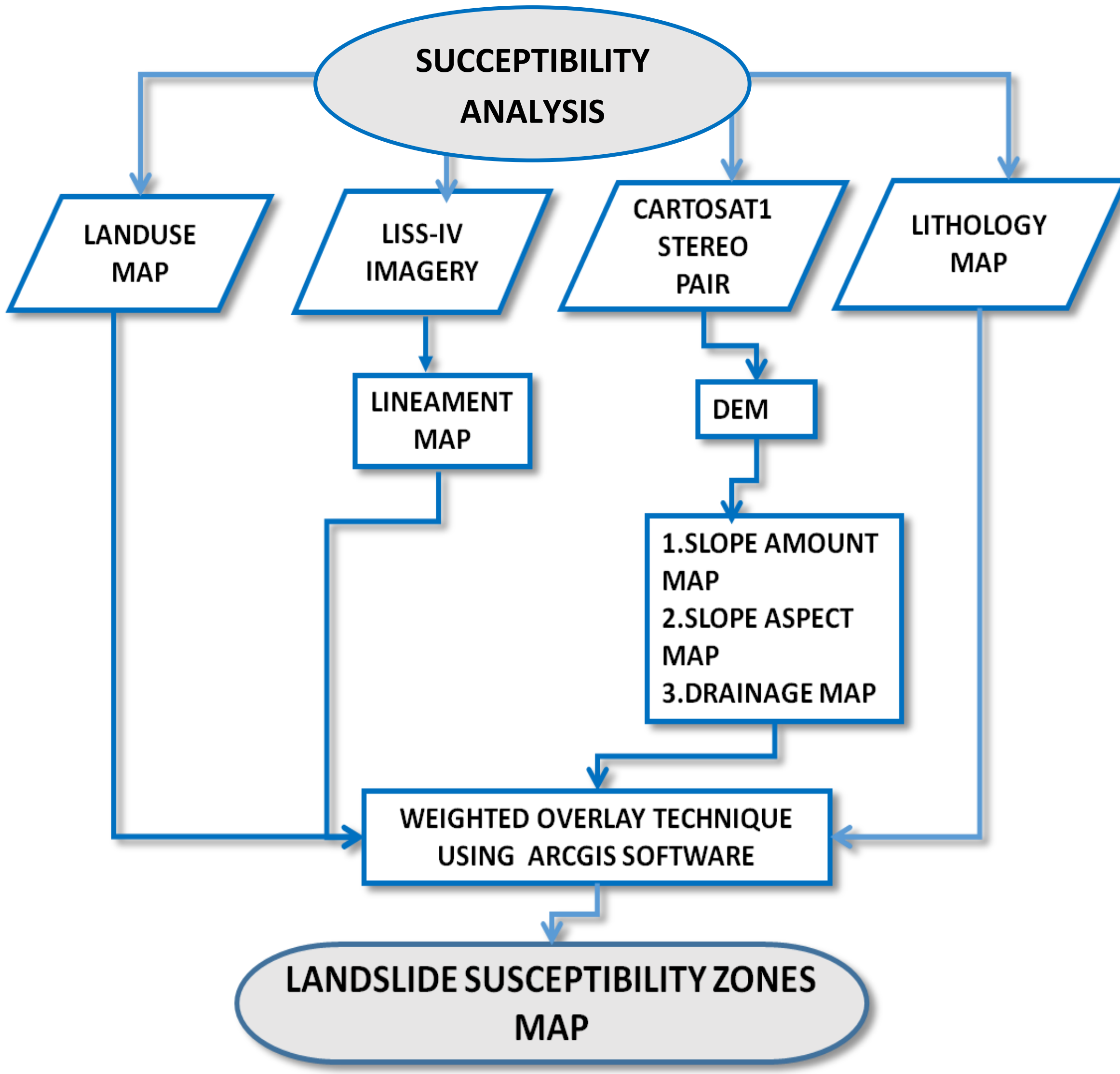

Figure 7: Flow chart of Methodology for Succeptibilty Analysis

4.2.1 Preparation of database for weighted overlay

The succeptibility zonation is carried out using eight layers namely-Slope, aspect, lithology, geomorphology, drainage, lineament, NDVI and land use land cover. The following map layers are chosen owing to their influence on landslides. Slope is the main factor that affects in increasing shear stress and also reducing shear strength. The higher of the slope is associated with the higher of the shear stress. It means that the probability of failure is getting bigger, i.e. higher slope areas are more pronounced to landslide activity then the lower ones, lineaments and drainage also have positive influence on landslide occurrence whereas vegetation decreases the susceptibility to landslides as higher the vegetation density lesser is the risk to slope failure as vegetation binds and holds the top and vice-versa, lineaments are indicative of zones of weakness or disturbances hence increase the probability of failure. Geomorphological landforms like dissected hills are more susceptible to landslides while others like piedmont zones are less susceptible than the prior stated geomorphological units. likewiswe several lithogolical units are more prone to landslides than others, lithology is parent material. it plays a role as slip surface. The hard and massive rocks are generally resistant to erosion (Anbalagan., 2001), e.g. granite rocks and limestone rocks. Apart from that, rock composed by sandstone is more vulnerable to erosion so that it is more susceptible to landslide. Hence these eight layers are considered owing to their influence on the occurrence of landslides. The lithology, geomorphology, land use and land cover map are all converted to raster and Euclidean distance is calculated for drainage and lineament and these are also converted to raster layers. It is noted that all the raster layers have same cell size, similar extent and the same projection in UTM. Then weightage is assigned to the maps for weighted overlay operation.

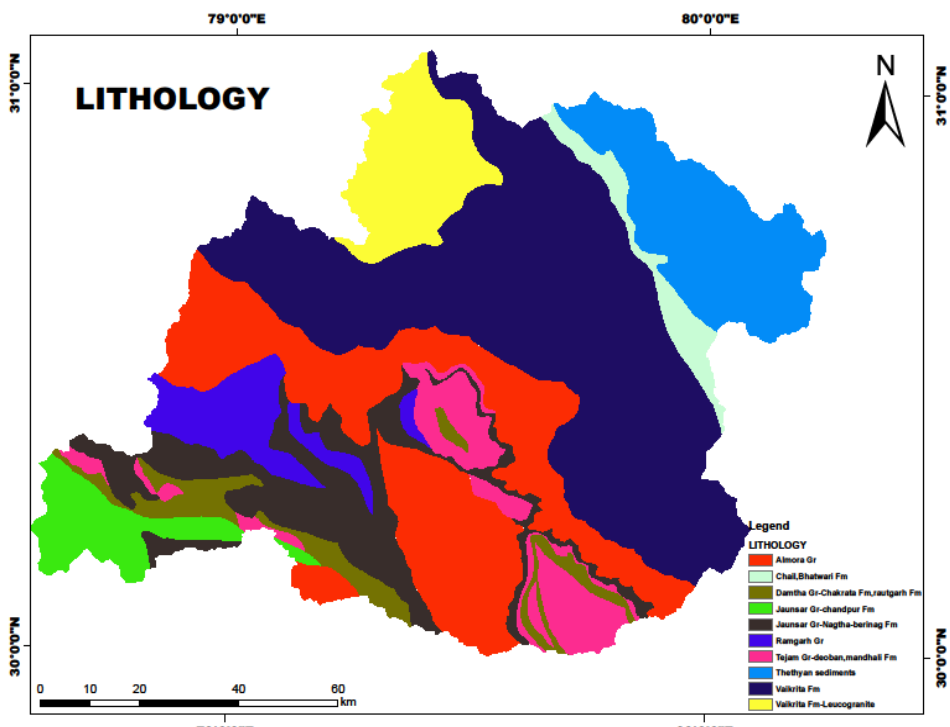

Figure 8: Litholgy Map of Alaknanda Valley(source:Rupke and Valdia, 2005)

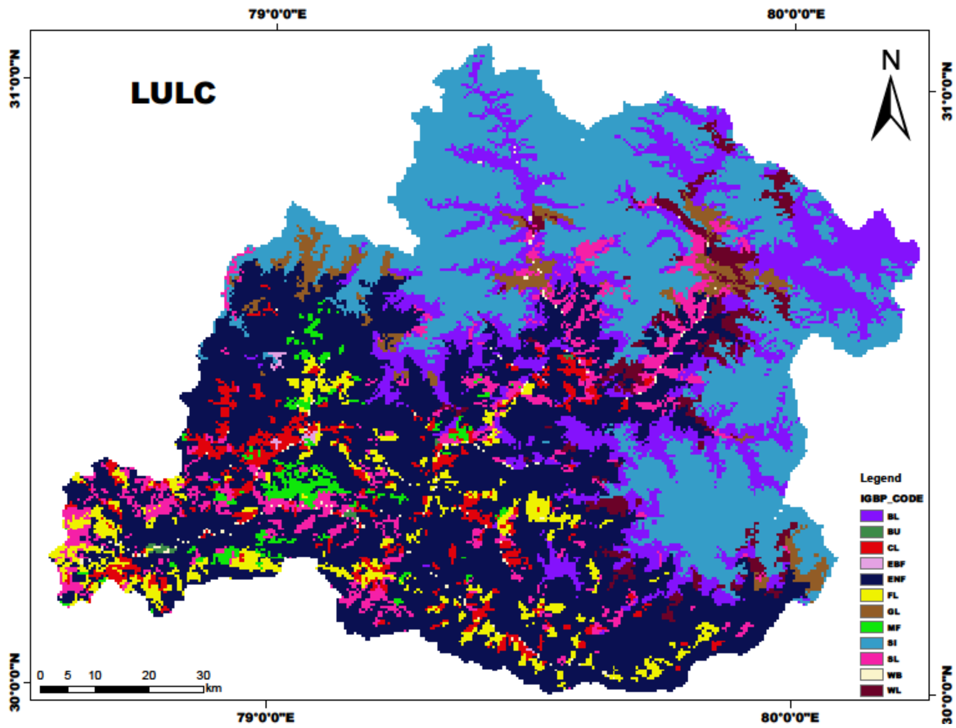

Figure 9: Land Use and Land Cover Map of Alaknanda Valley(source:IGBP, 2005)

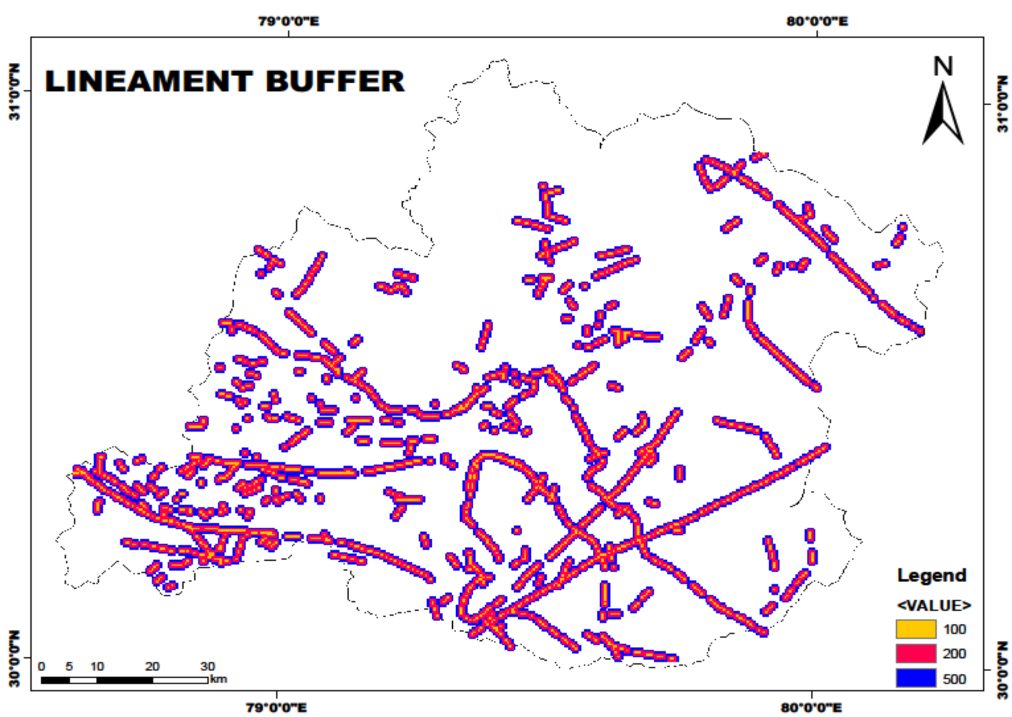

Figure 10: Lineament Buffer Map of Alaknanda Valley

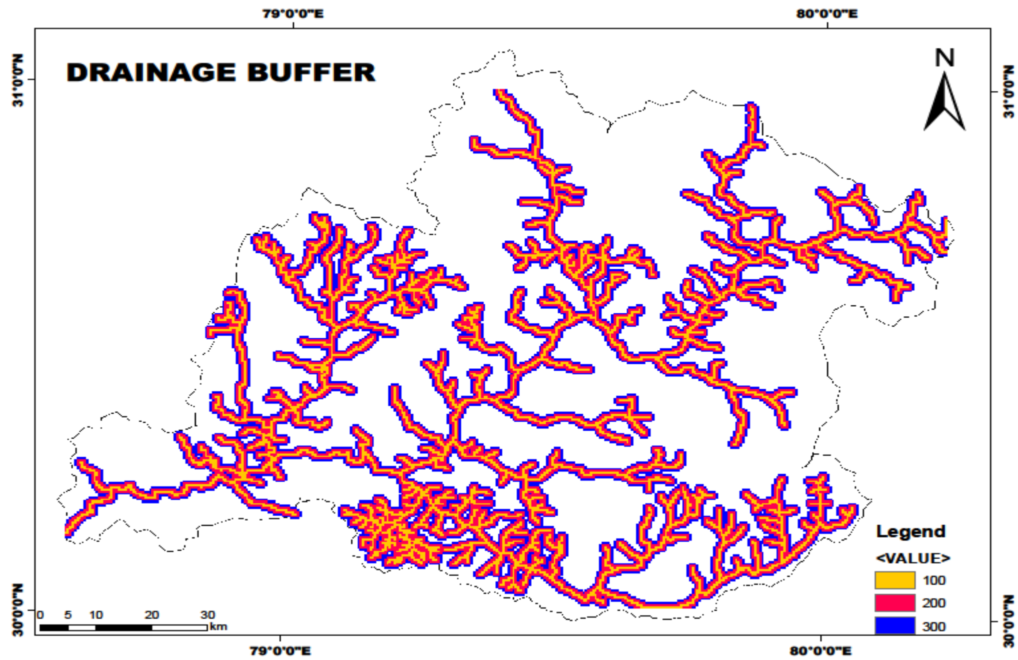

Figure 11: Drainage Buffewr Map of Alaknanda Valley

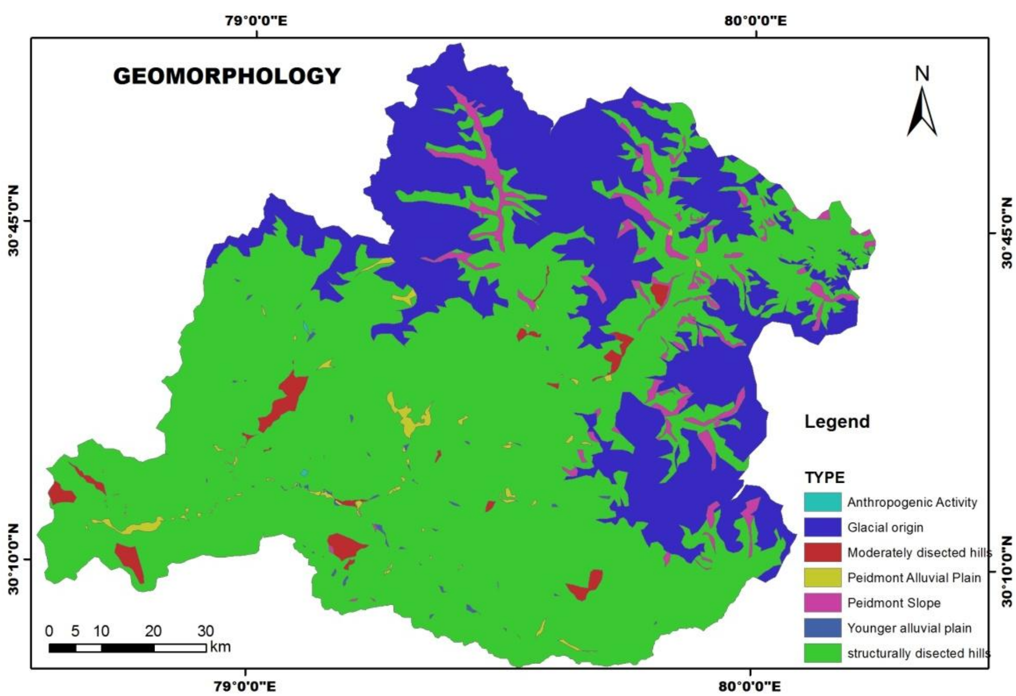

Figure 12: Geomorphology Map of Alaknanda Valley(source: Bhuvan, level-2)

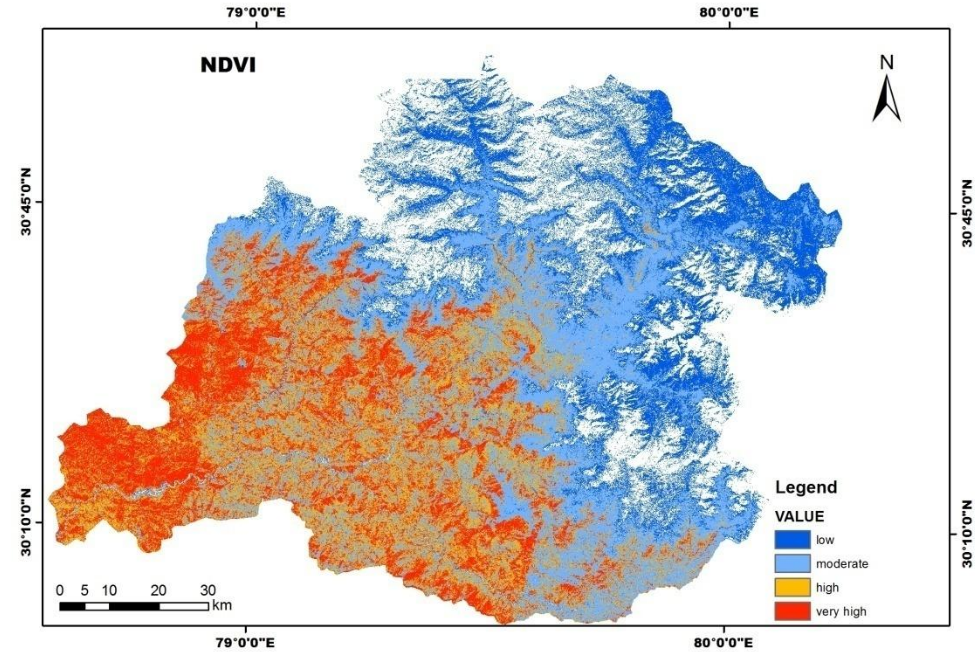

Figure 13: NDVI (Normalized Difference Vegetation Index) Map of Alaknanda Valley

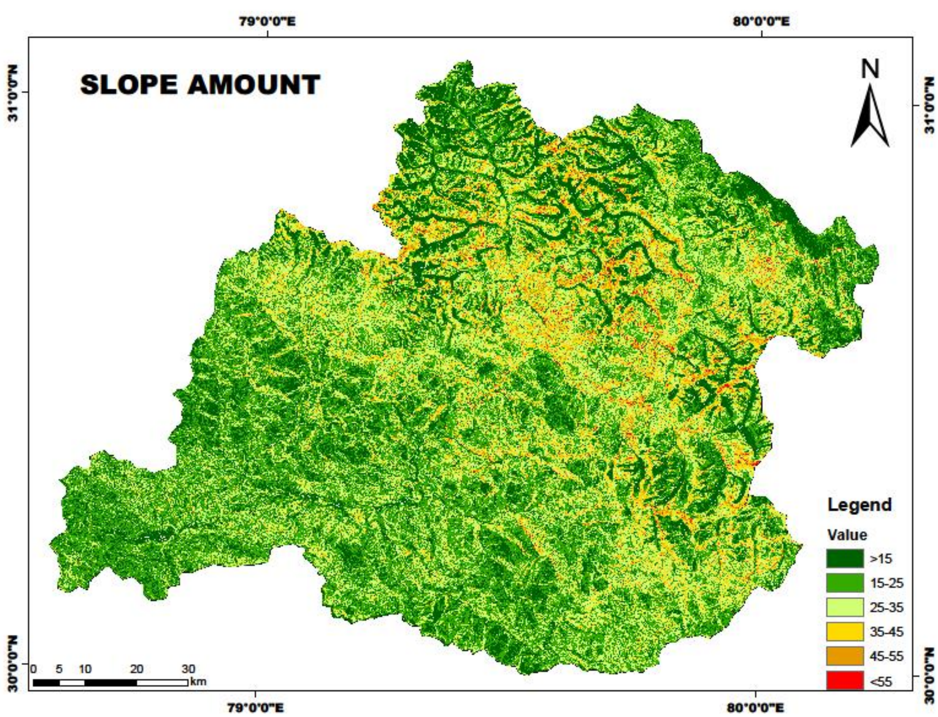

Figure 14: Slope Map of Alaknanda Valley (source: SRTM DEM 30m)

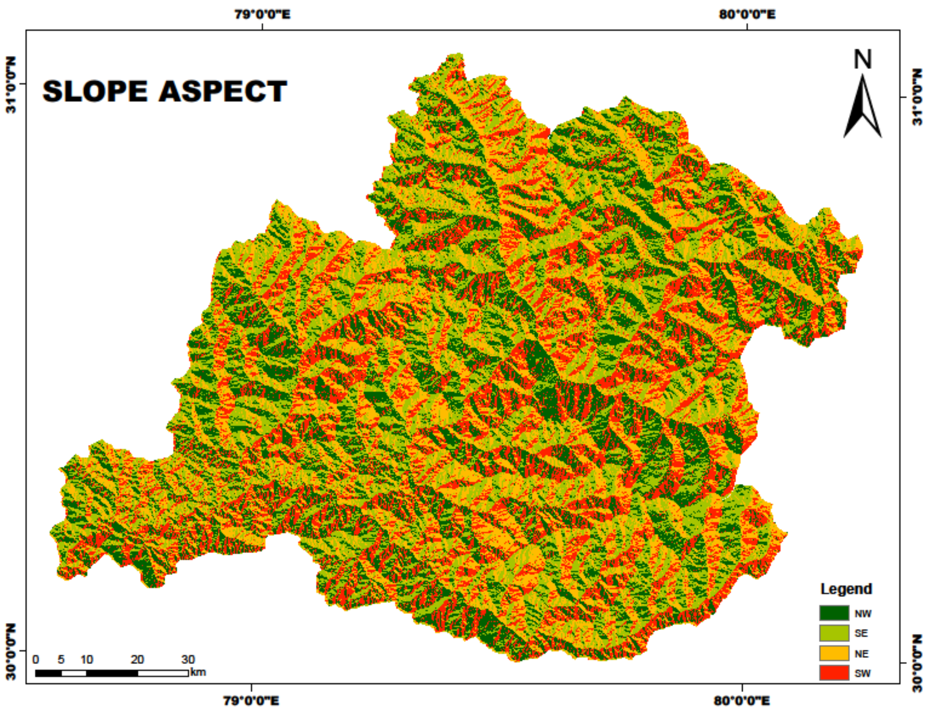

Figure 15: Aspect Map of Alaknanda Valley (source: SRTM DEM 30m)

4.2.2 Weighted overlay technique:

The weighted overlay technique is a map combination qualitative approach for landslide hazard zonation. The map combination approach for LSZ mapping involves a number of steps (Soeters 1996):

(i) Selecting the causitive factors and mapping of the causative factors.

(ii) prepration of thematic data layer with relevant categories of the factors.

(iii) Assigning weights and ratings to causitive factors and their respective categories.

(iv) thematic data layers combination.

(v) Preparation of LSZ map.

The pre-requisite for LSZ mapping is the preparation of thematic data layers pertaining to different causative factors. Commonly these factors include lithological factors, lineament, slope of the area, aspect of the slope, land use and land cover, and drainage in the area etc. (Kunango.D.P., 2009). The weights and influence assigned to each map layer depends upon the influence or importance of that map layer from the point of view of landslide occurrence, and the study area, i.e. the knowledge about the study area and the causative factors of landslide in the study area.

The weightage and influence assigned to each map layers and its parameters is described in (Table: 4). The highest influence is given to slope because it is observed that landslides are more prominent in high slope areas, the slope map is divided into six classes ranging from slope of less than 15 degrees to greater than 88 degrees and greater weights are assigned to high slope areas than the low slope areas. After slope drainage is assigned the second highest influence because of prominence of landslides along the drainage corridor, the drainage buffer map is prepared and buffer distance of 100m, 200m and 300m is considered and lesser buffer distance is assigned the highest weightage as the areas near the drainage are more prone to landslide activity, next the influence varies in decreasing order with lineaments, NDVI, geomorphology, aspect, lithology and LULC. Lineaments have been assigned higher weightage than the proceeding layers as they influence slope failures greater than other parameters, indicating weak zones or zones of disturbances. Lineament buffer is considered at a distance of 100m, 300m and 500m . the NDVI(Normalised Difference Vegetation Index) map is divided into four major zones and low ndvi areas are assigned higher weightage. In case of aspect map the SW and SE trending slopes are assigned greater weightage as more rainfall is received on these slopes, so landslide susceptibility is higher as compared to NE and NW slopes. For Lithology, Geomorphology and LULC map weightages are assigned according to susceptibility of respective areas to landslides, i.e. lithologies like shales and clay formations are assigned higher weightage than granitic ones, whereas regions like barren land, build up areas are assigned less weightage in comparison to the forest land areas.

Table 1: Weightage and Influence assigned

SLOPE	WEIGHTS	%INFLUENCE
>15	3	20
15-25	5	
25-35	6	
35-45	7	
45-55	8	
<55	9	
ASPECT	WEIGHTS	%INFLUENCE
NW	5	8
SE	8	
NE	6	
SW	7	
LINEAMENT	WEIGHTS	%INFLUENCE
100	7	16
300	6	
500	4	
DRAINAGE	WEIGHTS	%INFLUENCE
100	8	18
200	6	
300	4	
GEOMORPHOLOGY	WEIGHTS	%INFLUENCE
HIGHLY DISECTED STRUCTURAL HILLS	8	10
MODERATELY DISECTED STRUCTURAL HILLS	7	
GLACIAL ORIGIN	6	
PEIDMONT SLOPE	6	
PEIDMONT ALLUVIAL PLAIN	5	
YOUNGER ALLUVIAL PLAIN	6	
LITHOLOGY	WEIGHTS	%INFLUENCE
CHAIL,BHATWARI FM	9	8
TETHYAN SEDIMENTS	8	
VAKRITA FM-LEUCOGRANITE	7	
VAKRITA FM	7	
JAUNSAR GR-NAGTHA	6	
ALMORA GR	5	
RAMNAGAR GR	4	
TEJAN GR-DEOBAN	3	
JAUNSAR GR-CHANDPUR	2	
DAMTHA GR	5	
LULC	WEIGHTS	%INFLUENCE
CL	5	5
BL	7	
MF	3	
SL	5	
FL	6	
GL	5	
EBF	5	
ENF	3	
SI	4	
WB	4	
NDVI	WEIGHTS	%INFLUENCE
LOW	7	15
MODERATE	5	
HIGH	4	
VERY HIGH	2	

Weights were assigned on the basis of the experience of the experts on the subject and the study area. The weightage assigned will deviate from one expert to another and also from a region to another. Also the subjectivity in assignment of weights to every thematic data layer and to its categories is the major limitation of this approach. However the susceptibility map prepared broadly categorizes areas on the basis of their susceptibility to landslides into four major classes namely: very low, low, moderate, high and very high susceptible areas.

4.3 Automated Change Detection for Landslide Vulnerability Mapping

Landslide inventories are prerequisite for landslide hazard and risk assessment. So, far preparation of landslide inventories mainly relied on very time consuming and resource intensive conventional methods of remote sensing, that included visual interpretation of optical data aided by comprehensive field surveys (Behling, 2014). In the present study the detection of landslide vulnerable zones is carried out using remote sensing techniques in Alaknanda valley. The approach used for change detection requires pre-processing of the multi-temporal imageries; it requires precise spatial alignment of the two images with respect to one another. A pixel based change detection method is exercised for the study area. The overview of methodology adopted is listed as:

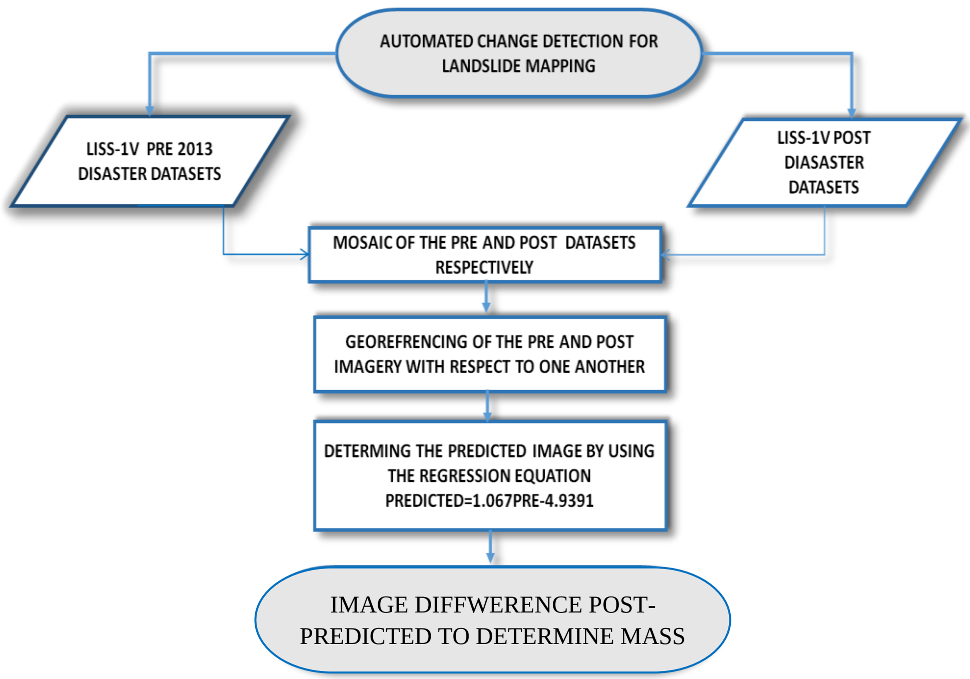

Figure 15: Overview of Methodology for Automated Change Detection for Landslide

4.3.1 Input datasets used

A comprehensive change detection system for landslide vulnerable zones mapping requires pixel based techniques for change demarcation of high resolution imageries.

The change detection analysis procedure was carried out for multi-temporal Liss-1V images i.e. pre Kedarnath 2013 disaster and post Kedarnath 2013 disaster. The pre disaster imageries used are all owing to the year 2011 and post monsoon and the set of post disaster imageries used are of 2013 post the Kedarnath event i.e. post monsoon. Firstly the images are orthorectified then two set of mosaic images are prepared by combining all the pre and post disaster imageries respectively.

4.3.2 Pre-processing

For efficient change detection the two set of mosaic imageries must completely overly, but it was noticed that there was a shift encountered in the pre and post mosaic image pair. To remove the observed shift from the data pair the pre disaster imagery was georefrenced with respect to the post disaster imagery. One more agility observed in the data pair was an increased brightness value in one of the imagery owing to the pre mosaic data(2011), hence histogram equalization was performed on the pre mosaic image to moreover equalize the contrast of the mosaic. However complete equalization of the contrast was not achieved but the quality of the mosaic was greatly improved in terms of contrast balancing with respect to the non-equalized mosaic.

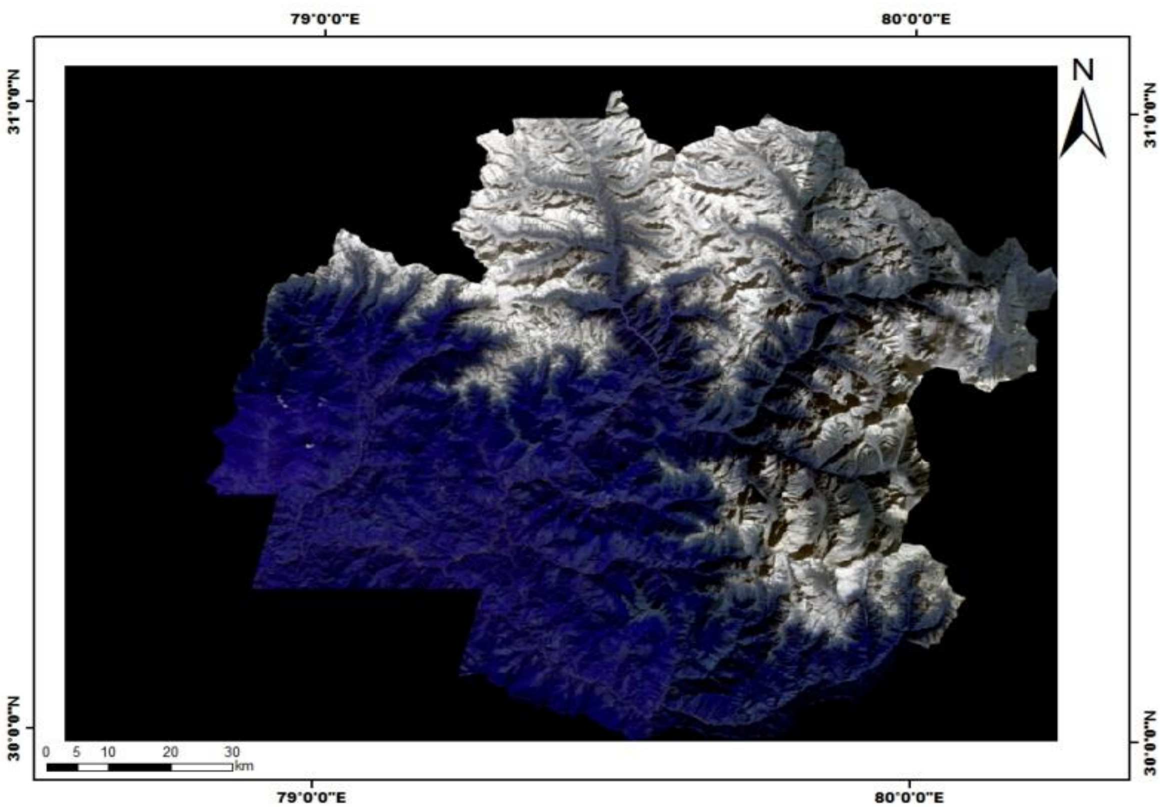

Figure 16: Post disaster mosaic imagery (2011)

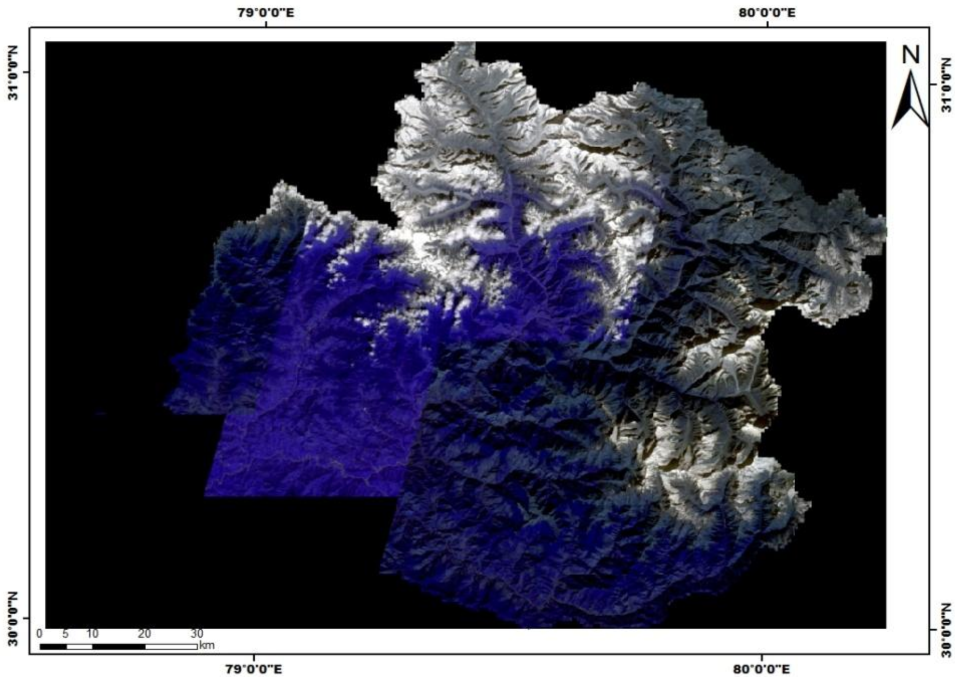

Figure 17: Pre disaster mosaic imagery before histogram (2013)

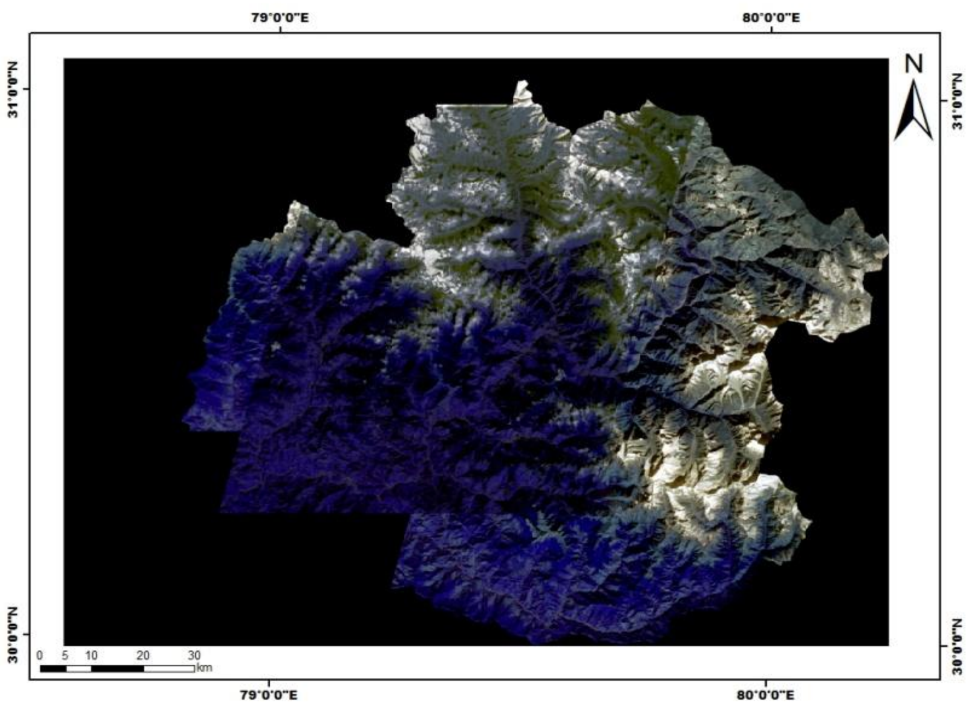

Figure 18: Pre disaster mosaic imagery after histogram eq1ualiosation

A statistical approach based upon pixel values of the two images is used for detection of mass wasting zones. The employed technique calculates the of spectral and textural change in the pixel values by arithmetic procedures such as, regression and image difference, and hence estimates the change of the transformed pixel values. In the present study a no of 70 pixel values are selected corresponding to both pre and post imageries from owing to the areas where change is not prominent using these 70 pixel values a regression equation is determined.

$$y=1.067x-4.9391 \tag{4.1}$$

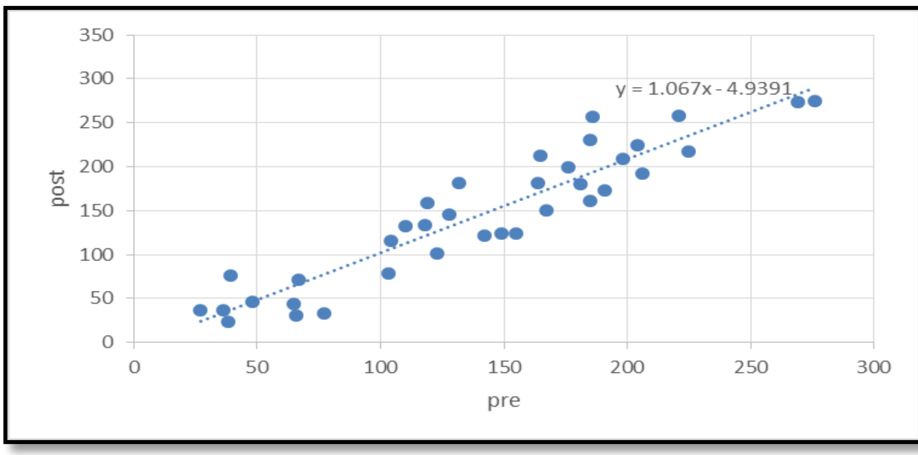

Figure 19: graph between pre and post imagery pixels

Using the regression equation predicted image is calculated:

$$\text{Predicted image} = 1.067\,\text{pre image} - 4.9391 \tag{4.2}$$

Image difference operation is then applied on the post and predicted image. The image difference technique uses the images of the same area, obtained from two times and subtracts the two pixels wise. Mathematically, the difference image is

$$Id(x,y)=post(x,y)-predicted(x,y), \tag{4.3}$$

Where (x,y) are the pixel coordinates. The resultant image Id, represents the intensity difference of the post and the predicted images. It works on the principal that change in land cover will result in changes in the radiance values and changes in radiance must be large as compared to radiance changes by other factors. Hence the highlighted changes between the post and the predicted images are a result of land cover mainly and are interpreted in terms of vulnerable zones for landslides.

.4.4 RAMMS (Rapid movement mass flow)

Estimating the debris flow run-out and related intensities (e.g. height and velocity) is important to link the hazard with the vulnerability and related losses of elements at risk to debris flows.

RAMMS (Rapid Mass Movements) is a dynamic numerical modeling software package developed by the Swiss Federal Institute for Snow Avalanche Research (WSL/SLF) originally to model snow avalanches (Buhler et al., 2011; Fischer et al., ̈ 2012). However, it has also been applied to model other types of mass movements like lahars (Quan Luna, 2007), rock avalanches (Schneider et al., 2010) and debris flows (Kowalski, 2008). The 2-D model is capable of predicting the run-out path, velocities, flow heights and impact pressures in a two(2-D) and three dimensional (3-D) domain. The flow model is therefore a abstraction of the quasi one-dimensional model, as discussed by Bartelt et al. (1999). RAMMS uses the Voellmy-Salm fluid flow continuum model (Salm, 1993) based on the Voellmy-fluid flow law (Voellmy, 1955) and describes the debris flow as a hydraulic-based depth-average continuum model. The flow resistance is divided into a dry-Coulomb friction (μ) and a viscous resistance turbulent friction (ξ).

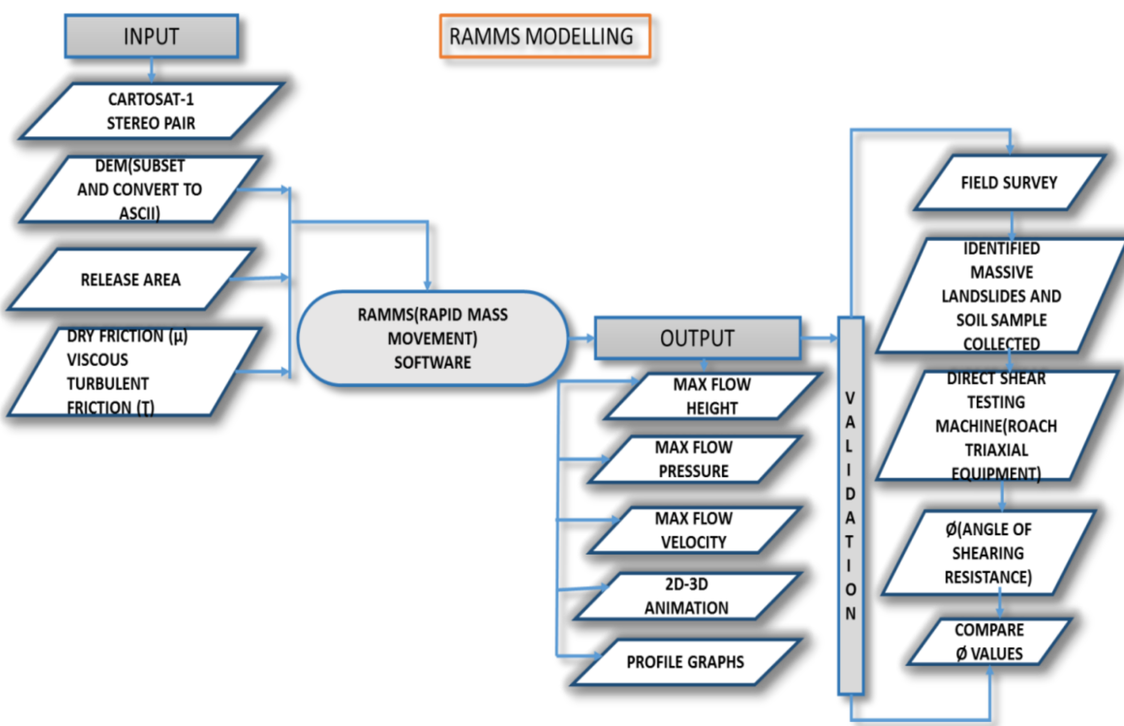

Figure 20: Flow chart of Methodology for RAMMS Modeling

4.4.1Principal:

RAMMS uses the Voellmy-Salm fluid flow continuum model on the Voellmy-fluid flow law (Voellmy, 1955) and describes the debris flow as a hydraulic-based depth-average continuum model. The flow resistance is divided into a dry-Coulomb friction (μ) and a viscous resistance turbulent friction.

$$\boxed{S = \mu\rho Hg\cos(\varphi) + \rho gU^2/\xi}$$

RAMMS uses the Voellmy-Salm fluid flow continuum model rooted on the Voellmy-fluid flow law (Voellmy., 1955) it therefore expresses the debris flow as a hydraulic-based depth-average continuum model. The flow resistance is divided into a dry-Coulomb friction (μ) and a viscous resistance turbulent friction.

Here,

þ= flow density (kg/m^3)

g= gravitational acceleration (m/s^2)

μ=dry friction (m/s^2)

Ø=slope angle

€=velocity squared drag coefficient (viscous turbulent friction)(m/s^2)

H-flow height (m)

U=flow velocity (m/s)

This model has found wide application in modelling of debris flows all over the world. One reason Vollemy is useful in debris flow modelling is that it only requires two parameters to calibrate. The turbulent term dominates the frictional behavior when the flow is moving rapidly and the dry friction term is useful when the flow is moving slowly, allowing the model to be approximately calibrated to observations of flow velocity and the stopping location of flow front.

The RAMMS environment uses three dimensions: x and y are the directions of the mass movement flowing down the topographic surface and the elevation is given by z(x, y), which is perpendicular to the profile. The gravitational acceleration vector in the three directions is given as g = (gx , gy , gz) and the time component is denoted as t. The flow is assumed to be moved in an unsteady and non-uniform motion and is characterized by two main flow parameters, which here incorporate the height of which is denoted as H(x, y, t) in meters (m) and the mean velocity denoted as U(x, y, t) in meter per second (m/s). The initial height is determined by the user when defining the source area of the debris flow as a polygon.

The final inputs used in this research to model are the following: a DEM, a source and entrainment area with their defined surface areas and heights; and the calibrated values for the friction coefficient μ, the turbulent coefficient _ and the entrainment coefficient K. the outputs generated include max flow height, max flow pressure, max flow velocity and 2D-3D animations and profile graphs

4.4.2 Field Survey:

The field survey on NH-58 highway was conducted and latitudes and longitudes of the major landslides observed in route were noted and soil samples were collected out of these 20 landslide records four major landslides were selected for RAMMS modelling.

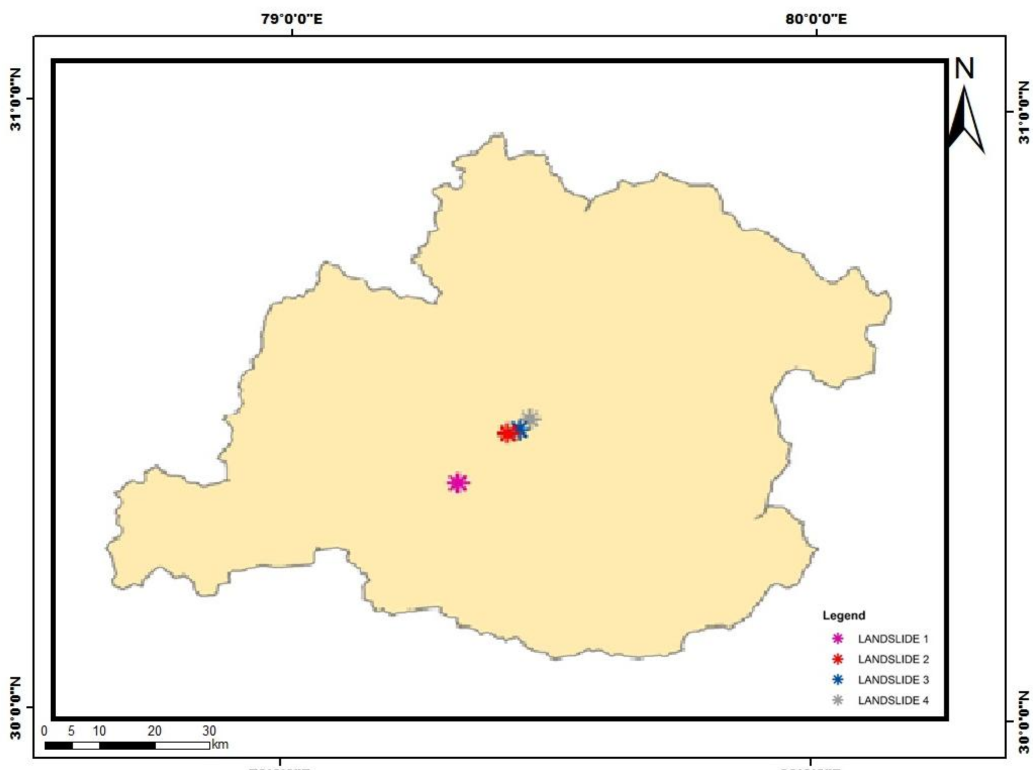

Figure 21: Landslide location map

Landslide: 1 Field photograph

Landslide: 2 Field photograph

Landslide: 3 Field photograph

Landslide: 4 Field photograph

4.4.3 Inputs for the RAMMS model:

For these four landslide locations corresponding cartosat-1 stereo pairs were ordered and 10m DEM was prepared using the Leica Photogrammetry Tool. The DEM prepared was then subset for the precise landslide locations and were converted to ascii.txt format so to be read by the RAMMS software.

The other inputs given to the RAMMS software are:

1. The extent area

2. The release area

3. The dry friction (μ)= 0.4m/s^2

4. Viscous turbulent friction(Ţ) or (€)=2000m/s^2

The outputs generated include max flow height, max flow pressure, max flow velocity and 2D-3D animations and profile graphs.

5 RESULT AND DISCUSSION

5.1 Intensity–Duration Thresholding Results

The log-log plot of maximum intensity (I in mm/hours) to total duration(D in hours) of rainfall events which resulted in landslides have been used to derive the I-D equation , by drawing a lower bound line to the graph, and the equation is expressed as

$$I=58.7\ D^{-1} \qquad 5.1$$

The equation can be used to determine the probable duration of events which can initiate slope failures. The events triggering landslide pertaining to the equation have wide dispersion in terms of duration and maximum intensity. The highest intensity value observed is 13.67mm/hour and the lowest is 0.11mm/hour The highest duration is recorded for the intensity value of 0.79mm/hour for 260 hours and the lowest duration of 30 hours for an intensity of 10.96mm/hours, proposing that a high intensity value results in slope failure with a short duration of rainfall whereas for low intensities a long duration of rainfall is required to initiate slope failure.

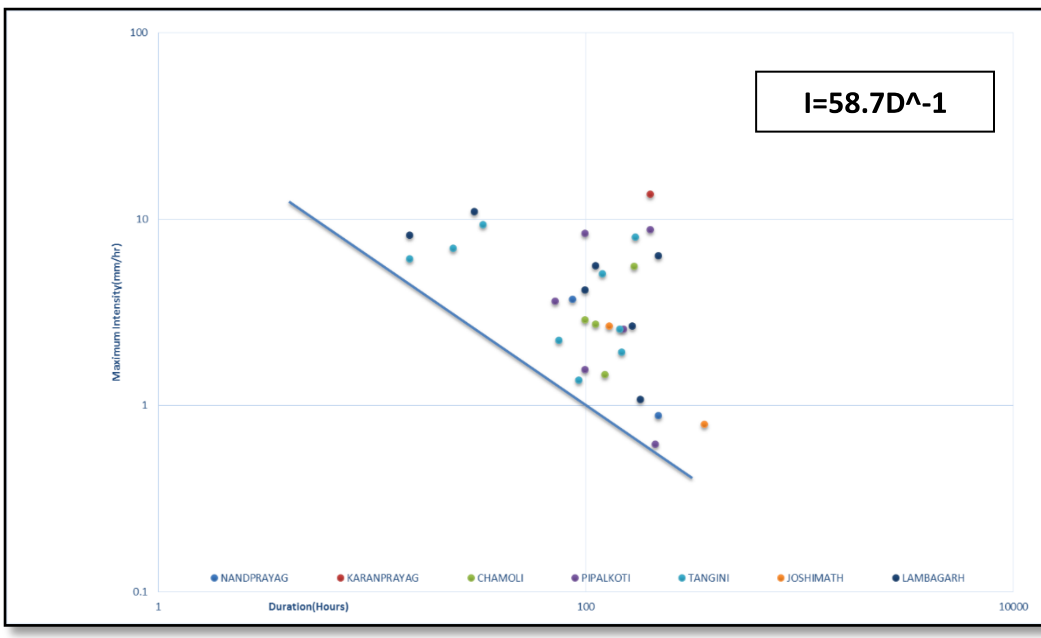

Figure 22: Log-Log Plot of Maximum Intensity to Duration

The validation of the I-D equation is carried out using the monsoon dates from 1st June to 1st October for the years 2013 and 2014. The following results have been obtained.

Table 2: Nandprayag, Chamoli, Pipalkoti and Tangini the following results are obtained for year 2013 and 2014.

TOTAL NO OF DAYS(2013)	NO OF LANDSLIDE DAYS		NO OF NON LANDSLIDE DAYS	
123	TRUE	FALSE	TRUE	FALSE
	17	3	98	5
TOTAL NO OF DAYS(2014)	NO OF LANDSLIDE DAYS		NO OF NON LANDSLIDE DAYS	
123	TRUE	FALSE	TRUE	FALSE
	14	2	100	7

Table 3: For stations Joshimath and Lambagarh the results obtained for year 2013 and 2014 are listed as:

TOTAL NO OF DAYS(2013)	NO OF LANDSLIDE DAYS		NO OF NON LANDSLIDE DAYS	
123	TRUE	FALSE	TRUE	FALSE
	29	4	81	9
TOTAL NO OF DAYS(2014)	NO OF LANDSLIDE DAYS		NO OF NON LANDSLIDE DAYS	
123	TRUE	FALSE	TRUE	FALSE
	23	2	86	12

Table 4: For the station Karanprayag the results obtained for year 2013and 2014 are listed as:

TOTAL NO OF DAYS(2013)	NO OF LANDSLIDE DAYS		NO OF NON LANDSLIDE DAYS	
123	TRUE	FALSE	TRUE	FALSE
	17	3	98	5

TOTAL NO OF DAYS(2014)	NO OF LANDSLIDE DAYS		NO OF NON LANDSLIDE DAYS	
123	TRUE	FALSE	TRUE	FALSE
	12	4	100	7

The error of commission for landslide days for the year 2013 is calculated as 15.26 and accuracy of prediction of landslide days for 2013 is 84.74% and the error of omission for non-landslide days is calculated as 6% and the accuracy of prediction is 94%. For 2014 the error of commission is 15% and accuracy is 85% and error of omission is 9% and accuracy 91%. Also it is noted that generally slope failures are initiated when a threshold value of about 1.8 is reached.

The overall error of omission is 7.41%, hence the threshold equation has successfully predicted non landslide lays by an accuracy of 92.59% and the error of commission is 13.84% i.e. the threshold equation has successfully predicted the landslide events by an accuracy of 86.15%

Thus the present study has established an I-D equation for rainfall induced landslides along the NH-58 highway and can be used to derive early warning for rainfall induced landslides. The utility of the equation is that at any instant of time using the prevailing rainfall intensity or the higher rainfall intensity value in the same event, if any, it is possible to determine the likely duration in which threshold will be crossed to initiate probable slope failure.

5.2 Result and discussion for Impact analysis

The susceptibility map obtained as a result of weighted overlay technique demarcates the Alaknanda valley into four zones based upon the susceptibility of landslides. The five zones include very low, low succeptible area, moderate succeptible araes, high and very high susceptible zones. On analyzing the map it is observed that the high susceptibility zones are mainly concentrated towards high slope areas and drainage corridor in the study area.

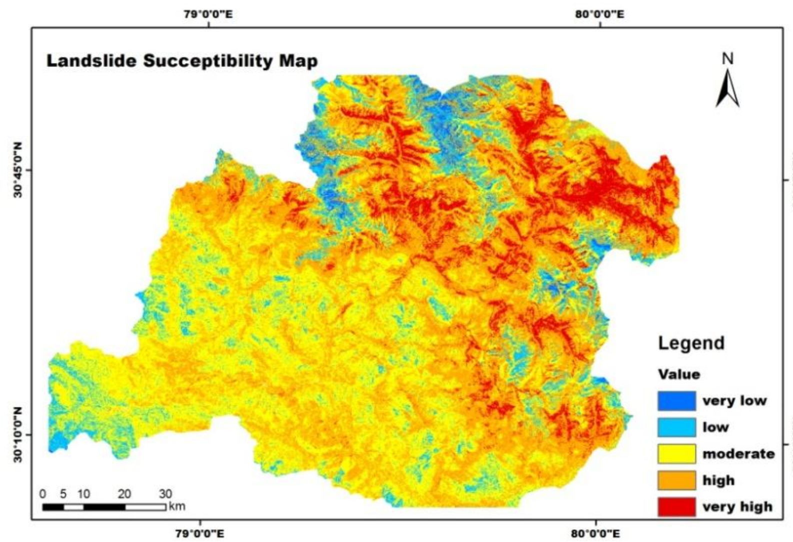

Figure 23: Landslide Succeptibility Map of Alaknanda Valley

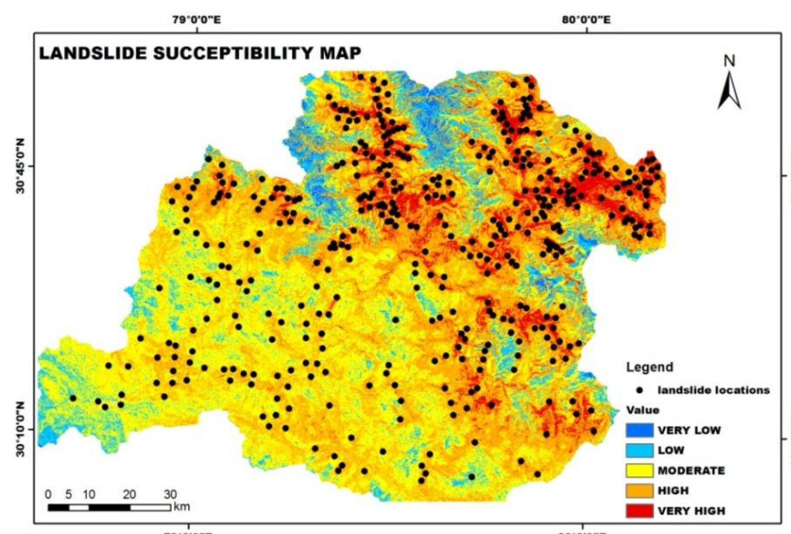

Figure 24: Landslide Susceptibility Map of Alaknanda Valley with landslide locations.

The Susceptibility map is validated based on the landslide locations which are obtained from Google earth. A total of 244 major landslide location points were chosen from Google Earth and it was observed that out of the 244 landslide point locations 5 landslide points fall under the low susceptible area, 33 fall under the moderate susceptible area, 79 come under the very high susceptible zone and the rest 127 landslide locations are under the high susceptible zone. Hence it is noted that 84.4% of the landslide points are encompassed in the high and very high susceptible zones while the remaining 15.6% of points lie under the low and moderate susceptible zones, thus indicating that majority of landslide points falling under the high and very high susceptible zones.

The vulnerability map obtained as the result of automated change detection techniques demarcates areas of high change as vulnerable zones for landslides.

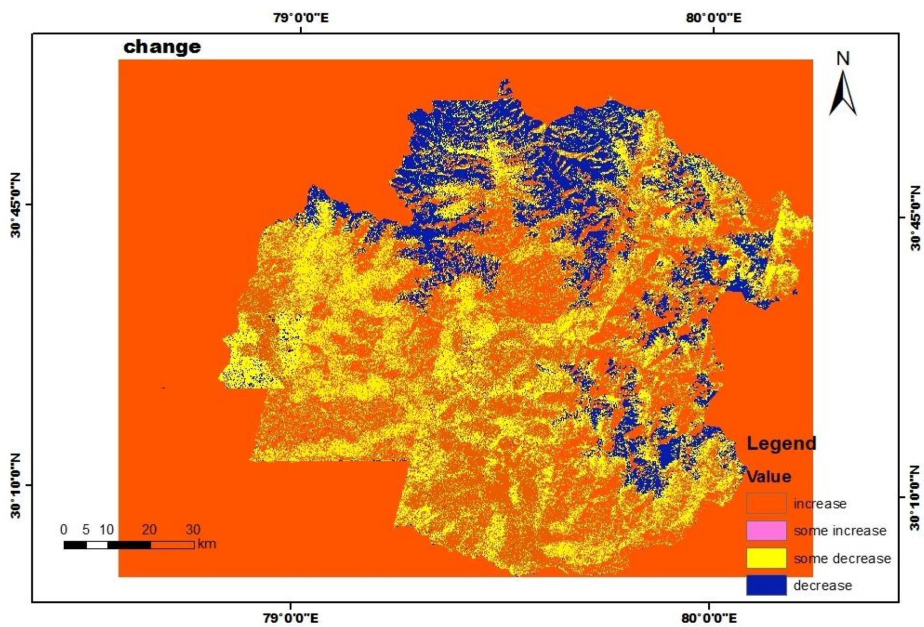

Figure 25: MassWasting map

The Mass wasting map when compared with the susceptibility map illustrates that the high change areas are majorly towards high slope zones and the drainage course same as observed in case of the landslide susceptibility map. Hence it is noted that results obtained from automated change detection and weighted overlay technique correspond with one another and depict that the high susceptible areas for landslide are majorly trending towards high slopes, and the drainage course.

5.3 Result and discussion for RAMMS modelling

The RAMMS software was used to simulate the landslide scenario and the results obtained from ramms modeling are presented in the form of 2-D animations of the maximum height scenario that existed at the time of sliding, the maximum velocity conditions at the time of sliding and the maximum pressure conditions at the sliding time. The plots of altitude and velocity are also generated to determine the altitude and velocity of the sliding material.

The modelling results for landslide:1 a debris flow slide situated in between Nandprayag and Chamoli are discussed.

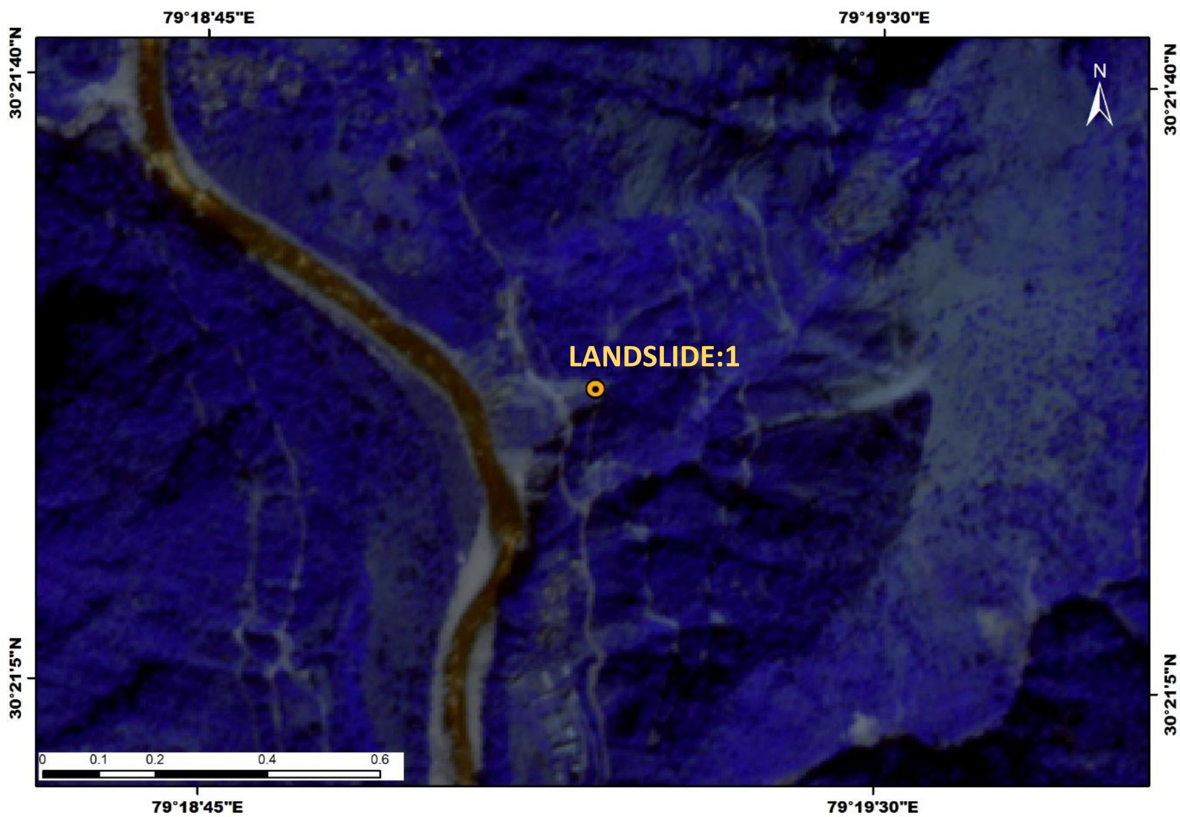

Figure 26: Landslide:1 location on Liss-1V image

From the altitude and velocity plots for the landslide one it is observed that the maximum height of the sliding material is 1270m and the maximum velocity attained by the sliding material was around 41m/s. From the two dimensional animations it was observed that the velocity at the time of sliding ranged between 6m/s to 41m/s, the height values were between 5m/s to 33m/s and the pressure at the time of sliding ranged between 577kpa to 3462kpa for the upper profile portion of the sliding area. From the animations it was observed that there is a cut in slope, so for the portion of the slide below the slope cut the maximum velocity attained was again around 41m/s and the maximum height and altitude values are 12m and 1032m respectively.

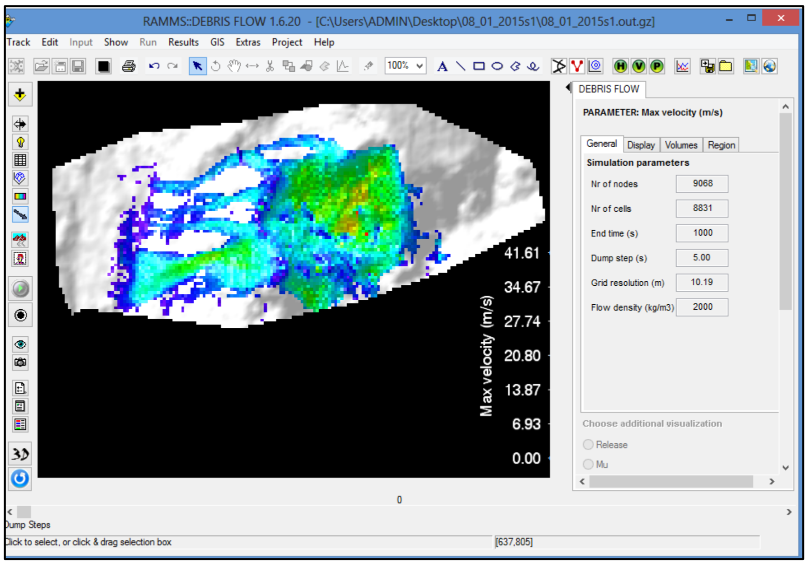

Figure 27: 2-D animation of the velocity condition at sliding time

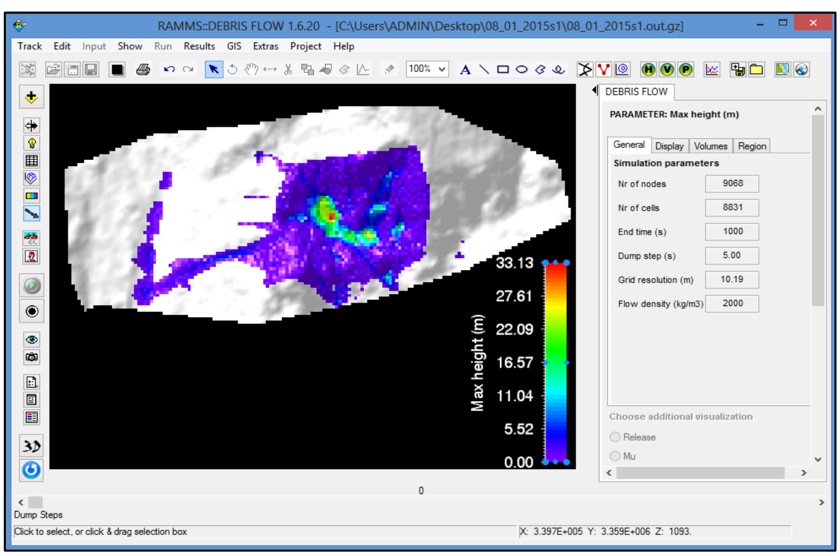

Figure 28: 2-D animation of the height at sliding time

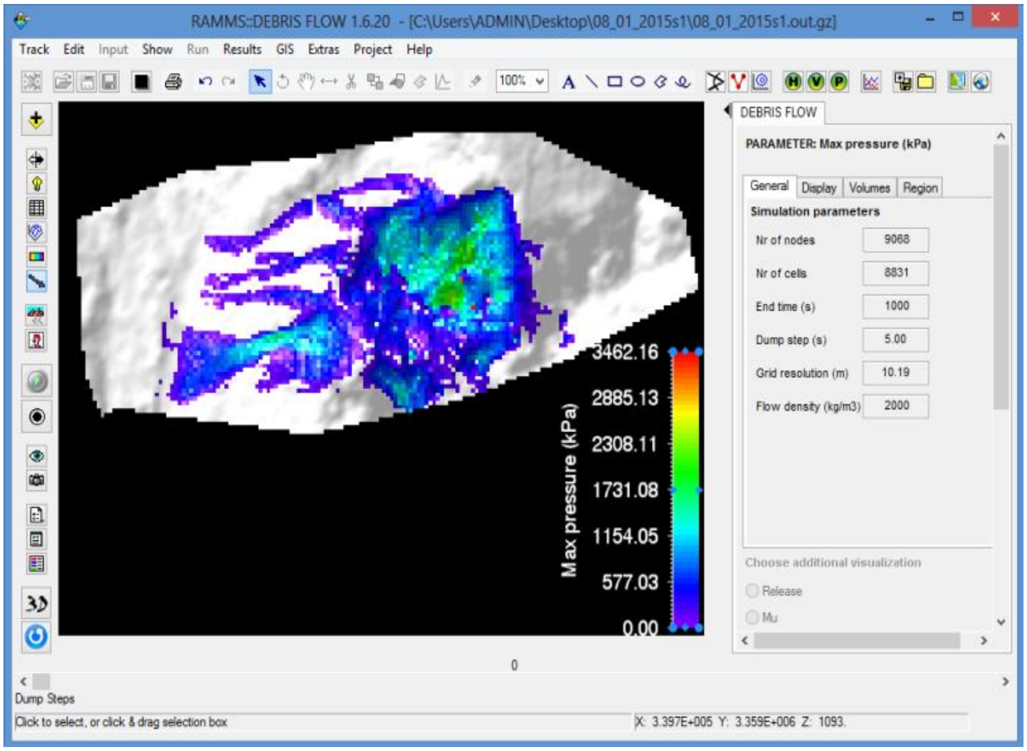

Figure 29: 2-D animation of the pressure condition at sliding time

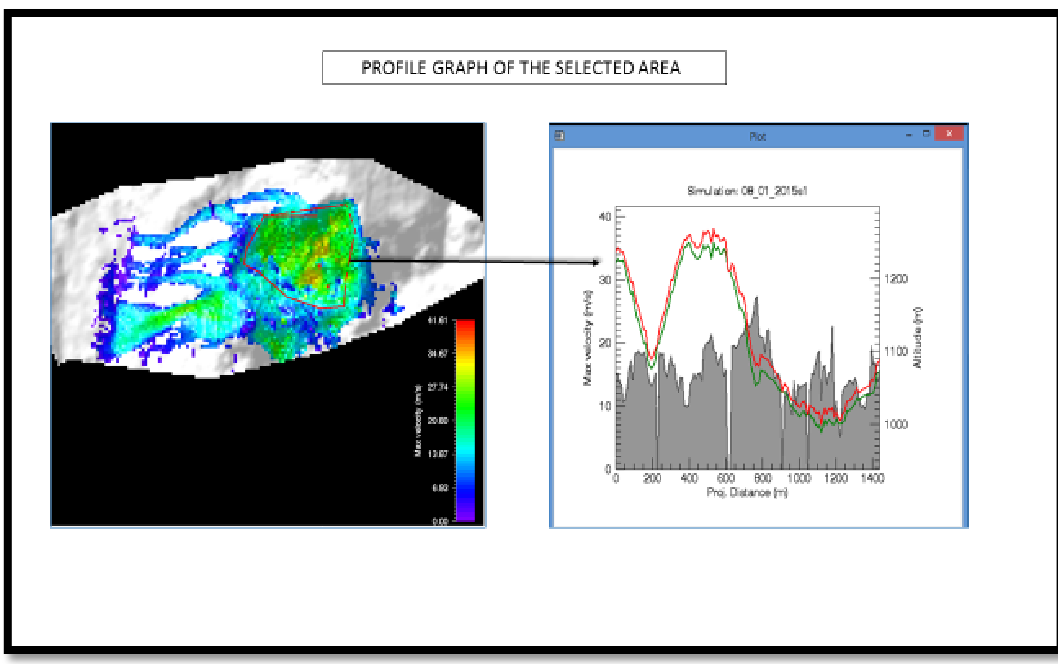

Figure 30: Profile Graph: 1 showing maximum velocity and altitude

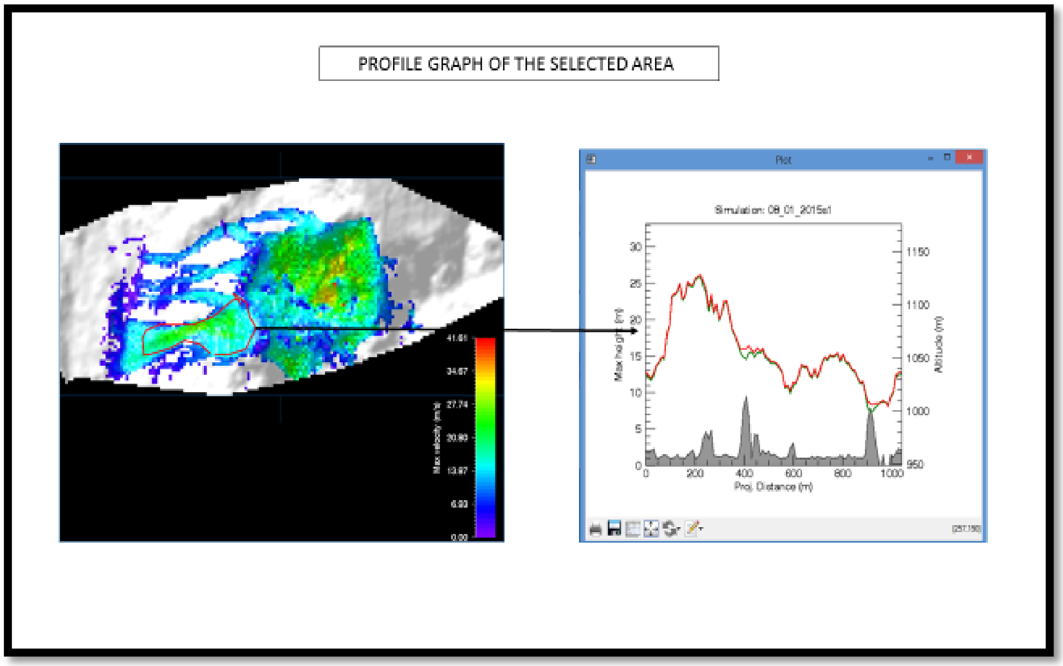

Figure 31: Profile Graph: 2 showing maximum velocity and altitude

The results obtained by the ramms software are analyzed and validated based upon the input parameters entered for running the model. To validate the results, the best-fit parameter is determined and used for validation. The µ i.e. dry friction value is used to validate the results. The value of M used for model generation was 0.2m and the value of dry friction (µ) obtained from the direct shear testing machine (Rocks Triaxial Equipment) for the soil sample obtained from field for the landslide: 1 was 0.3m. The two values of cohesion hence are nearby enough hence validating the ramms results.

Another analysis of result is carried out based upon the slide image and the 2-d animation similarity. It is observed that the two show a similar pattern, the 2-d animated profile for landslide: 1 shows a slope cut which is indicative of the road when compared with the Liss-1V image, devising the scenario at time of slide. Hence the ramms model successfully models debris flows in the study area and is useful to determine parameters that can help to predict the runout extent and its affects and hence be used to predict run out zone for slides and implement precautionary measures.

CONCLUSION

The present study has established intensity-duration based precipitation threshold for Alaknanda valley. The intensity- duration based precipitation threshold equation which is I=58.7 D^-1. On validation of the equation it was observed that the accuracy of the I-D equation for the prediction of landslide events is obtained to be 86.15% and for non-landslide events it is 92.59%. The Intensity-duraion based empirical threshold described are the fundamental element of the real time warning system. The study essentially focused on establishing a threshold for landslides based on the intensity and duration of the corresponding landslide triggering rainfall events. The TRMM(Tropical Rainfall Measuring Mission) 3B42 V.7 has been used as the source of rainfall intensity and peak intensity on the day of event was considered. The present study was undertaken because rainfall is the major triggering factor landslides in Alaknanda valley as it leads to increase in pore water pressure and decrease of cohesion are the main factors of slope failure, along with percolation of water into weak zones. The utility of I-D based rainfall threshold is that any instant using the prevailing rainfall intensity value the likely duration in which threshold will be exceeded can be determined. Thus it can be used to issue early warning to areas which are susceptible to slope failures.

Automated change detection carried for Alaknanda valley helped in identifying areas of mass wasting as regions with high change percentage. Also the mass wasting regions were noted to be prominently along the drainage and the high slope areas. The susceptibility mapping for Alaknanda valley classified the entire valley into five major zones namely- very high succeptibilty, high, moderate, low and very low landslide susceptible zones or regions. It was noted that the majority of the study area falls under very high succeptibility, high and moderate landslide susceptibility areas. On overlying the landslide locations it was observed that 84.4% of the landslide points fall under the very high and high susceptible areas whereas 15.6% lie under moderate susceptible zone. On comparison of the mass wasting map and the landslide susceptibility map it is seen that both correspond in accordance to high susceptible zones situated along high slope areas.

The results obtained from RAMMS modelling are validated on the basis of the dry friction values input to the model and derived from soil testing of the landslide field soil sample. The values closely fit to validate the RAMMS result, also the 2-D animation of the landslide and the

LISS-1V(18th Oct 2013) image both depict the landslide as having a slope break which from the satellite image is verified as the road passageway.

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