LANDSLIDE SUSCEPTIBILITY MAPPING OF LUNGLEI TOWN AND ITS VICINITY IN MIZORAM

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

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BY

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Submitted

In partial fulfillment of the requirement of the Degree of Doctor of Philosophy in Geology of Mizoram University, Aizawl.

DEPARTMENT OF GEOLOGY

MIZORAM UNIVERSITY

(A Central University established by an Act of Parliament)

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This is to certify that the thesis entitled "Landslide Susceptibility Mapping of Lunglei Town and its vicinity in Mizoram" written by Cory Lalbiakzuali for the award of Doctor of Philosophy in Geology has been written under my supervision.

She has fulfilled all the required norms laid down under the Ph.D regulations of Mizoram University. The thesis incorporates the student's bonafide research and that these have not been submitted for award of any degree in this or any other University or Institute of learning.

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DECLARATION

I, Cory Lalbiakzuali, hereby declare that the subject matter of this thesis is the record of work done by me, that the contents of this thesis did not form basis of the award of any previous degree to me or to do the best of my knowledge to anybody else, and that the thesis has not been submitted by me for any research degree in any other University/Institute.

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I dedicate this thesis to my parents.

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ABSTRACT

LANDSLIDE SUSCEPTIBILITY MAPPING OF LUNGLEI TOWN AND ITS VICINITY IN MIZORAM

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Landslide is a downslope movement of a mass of debris, soil, rock or earth material which takes place under the influence of gravity. (Varnes, 1978; Cruden, 1991; Cruden and Varnes, 1996). Landslides can be triggered by variety of natural phenomena that causes a rapid increase in shear stress or decrease in shear strength of slope-forming materials, such as earthquakes, rainfall, rapid snow melting, storm waves and volcanic eruptions (Dai *et al*., 2002; Guzzetti *et al*., 2005). Landslides are triggered by both high intensities and short duration rainfall (Glade, 1998) as well as prolonged rainfall (Church and Miles, 1987). Landslides are one of the geological processes which causes destructions not only to roads, railway tracks, bridges, and houses but also leads to loss of life. Therefore, landslide susceptibility mapping is very much needed for identification of potential and probable landslide areas.

In North-east India, several slides have been reported and especially in Mizoram over 1000 slides have been reported in the past. Though several landslides occur every year, some of these landslides are just minor slips. On the other hand, some landslides are disastrous and cause loss of life, damage to property and disruption of communication and transportation systems, and destruction of natural resources. The landslides that have occurred in recent years have taken place in areas close to settlements burying the houses with debris. 2018 and 2019 landslides that took place within the study area can be referred as a tragic events because many houses were shattered and even caused loss of lives. With increase in population and developmental activities it can be foreseen that urban development will be outstretch to areas susceptible to landslides. Hence, it is necessary to study the area to identify safe zones for urban development and identify the landslide prone areas so as to regulate and impliment measures for strengthening the slope in order to prevent future failure.

The present study aims to prepare a landslide Susceptibility map of Lunglei town and its vicinity with an aerial extent of 66.82 km^2, located in the southern part of Mizoram. Geographically, it is situated between the co-ordinates of $92^o42'45''$ E - $92^o50'05''$ E longitudes and $22^o48'18''$ N - $22^o56'55''$ N latitudes. and covers an area of 66.82 sq.km. It is accessible by National highway 54 and is 168.8 km from the city of Aizawl. The area consists of a series of NW-SE trending anticlines and synclines plunging in N-S directions. The anticlines are overturned consisting of moderately dipping Eastern limb while the western part is characterized by sharp ridgelines and vertical cliff face as a result of intense weathering and erosion of highly sheared rocks. The main litho-unit of the study area comprises of a repetitious sequence of argillaceous and arenaceous sedimentary rock of the Surma Group of rocks. The sedimentary formations vary from fine grey sandstone to fine to medium brown colored sandstone alternation with shales with varying proportions of clay and silt size particles. Based on the stratigraphic framework of Mizoram the rock exposure in the study area is divided into two groups namely the Upper Bhuban and Middle Bhuban formation of Middle to upper Miocene.

As mentioned earlier, the present study is an attempt to assess the landslide susceptibility of Lunglei town and its vicinity by GIS technique using Frequency Ratio method . The preparation of Landslide Susceptibility Zonation Map (LSZM) of Lunglei town and its vicinity was carried out in six steps. i) data collection ii) database generation iii) preliminary analysis, iv) validation v) evaluation of the relationship between the landslides and input data and vi) final preparation of Landslide Susceptibility Method.

The thesis comprised of five chapters such as chapter-1: Introduction, chapter-2: Geological setting, chapter-3: Methodology, chapter-4 : Results and discussion, chapter-5: Summary and conclusion.

In chapter-1 we can find the detailed introduction of the studies employed for this research. It includes a brief description of natural disasters and some basic ideas of Remote sensing and GIS. Explanation of landslide hazards and some historical landslides records of India and specifically Mizoram is available in this chapter. The types of landslides, causes and preventive measures are also mention for general understanding of landslides.

Chapter 2 comprise of the regional geology and geology of the study area. The present area of interest is situated in the Southern part of one of the North-south trending anticline formed as a result of the Indo-Myanmar oblique collision constituting the Southern extend of the Indo Burma Range (IBR). The main geologic features and processes responsible for its existence are the Himalayan Ranges, the Bengal Basin, Shillong Plateau, Surma Basin, and Indo-Burma Ranges (IBR). This chapter explain the Himalayan ranges, the Bengal Basin, Shillong Plateau, Indo-Burman ranges, Surma basin and general geoogy of Mizoram. The Himalayan ranges was formed due to the collision of Indian and Eurasian plates which resulted in closure of the Tethys Sea. The mountain range consists of litho-tectonic zones, separated by thrust and normal faults (Gansser, 1964). The Sub-Himalayan lithotectonic zone consists of the foreland basin sediments eroded from the still rising orogen in its northern front (Parkash et al., 1980). The mountain range consists of litho-tectonic zones, separated by thrust and normal faults (Gansser, 1964). The Sub-Himalayan lithotectonic zone consists of the foreland basin sediments eroded from the still rising orogen in its northern front (Parkash et al., 1980). The Shillong plateau is bounded by the Garo-Rajmahal trough fault to the west and the Dauki fault in the south(Johnson and Alam, 1991). "Late Mesozoic and Cenozoic sedimentary rocks drape portions of the southern Shillong plateau and generally dip south in a monocline. The contact between the Shillong plateau and the Sylhet trough is indicated by the poorly exposed Dauki fault. The Indo-Burmese Ranges occurring along the eastern margin of the Indian sub-continent are a clear representation of oblique collision of the Indian and Eurasian plates. Early Tertiary syn-orogenic sequences, which have been deformed into imbricate thrust zones are the principal constituent of the Indo-Burmese Range and are prominentgeo-tectonic elements of South Asia. The Neogene Surma basin is bounded by the post-Barail unconformity, subsequently faulted (Kaladan fault) to the east; the E-W Dauki fault and NE-SW Disang thrust to the north and northeast; the NE-SW Sylhet fault (Nandy *et al.*, 1983), also term as the 'Hail – Hakula' (Ganguly, 1993) lineament and Barisal-Chandpur high concealed below the alluvium of Bangladesh (Sengupta, 1966) to the west and north west. Mizoram is considered to be a major part of Neogene Surma basin which constitutes the southern extends of the basin. The main rock facies exposed in the Mizoram area of the Surma Basin are sandstone, siltstone, shale mudstone and their admixtures in various proportions and few pockets of shell limestone, calcareous sandstone and intra-formational conglomerate (Tiwari and Kachhara, 2003).

Chapter 3 includes the methodology employed for the study. Statistical method also known as Frequency Ratio method is used for calculating the landslide susceptible zones of the study area. The basic data sources are the Survey of India Toposheets (1:50,000 scale with 20m contour interval), digital elevation model obtained from Alospalsar (www.landsat.org) as free download, landslide inventory map was prepared by extensive fieldwork, rainfall data obtained from directorate of agriculture and other data needed for the preparation of thematic layers were also obtained from Mizoram Remote Sensing Applications (MIRSAC). The methodology for the preparation of landslides susceptibility map involves the preparation of digital database of spatial data which are related to landslides, classification and reclassification of the data, intersect analysis to calculate the frequency ratio assigning the calculated frequency ratio to the thematic layers, weighted sum analysis and calculation of landslide susceptibility index, and Suitable classification of landslide susceptibility and validation. Quick bird and world view satellite imagery having spatial resolution of 0.8 m obtained from Mizoram Remote Sensing Application Centre (MIRSAC) and Resourcesat-2: LISS-III was used for the preparation of thematic layers needed for the study. The thematic maps for the causative factors was prepared by extracting the information from Survey of India Toposheet and Satellite imagery.

The results and discussion of the study was the main component of Chapter 4. The relationship between the landslide occurrence area and the landslide related factors could be deduced from the relationship between areas where landslides had not occurred and the landslide related factors. To represent this distinction quantitatively, the probability likelihood (frequency ratio) was used. The probability likelihood (frequency ratio) is the ratio of the probability of an occurrence to the probability of a non-occurrence for given attributes (Bonham-Carter 1994). Field data like landslides points which was collected by handheld gps was used for the preparation of Landslide Inventory map of the study. 152 landslides recorded were plotted as point features on the georeferenced toposheets in ArcGIS. The relationship between landslides and each causative factor was calculated using the frequency ratio method. After finding out the frequency ratio, in order to prepare the final landslide susceptibility map, the thematic layers of the causative factors such as slope, drainage density, distance to drainage, landuse/landcover, plan curvature, structure and lithology were again reclassified and the landslides susceptibility zones for the study area was generated by overlaying the thematic layers and landslide occurrence points. The calculated frequency ratio was entered as new values for each classes using the spatial analyst tool in ArcGIS. The pixel size of the reclassified layers were 30×30m.

The validation of the map is done whether the predictions of susceptible zones matches the expected results. For validation of the LSM, the reclassified map was converted into vector layer and 25% of the landslides not used for calculating the frequency ratio were used. Intesect analysis was carried out again to find out how many of these landslides (ie.38 landslides or 25%) falls in the landslide susceptibility zones. After validation, the final Landslide susceptibility map was generated by repeating all the processes such as reclassification, intersect analysis and ovelay analysis. The percentage of landslides falls in high and very high zones yield good result and majority of the area is covered in these zones.

The frequency ratio (FR) values were calculated for each class present in whole causative factors based on the relationship with the landslide inventory map. The relationship results in weights, which can directly be evidence for the influence of each class in a causative factor for the landslide susceptibility. Among the different causative factors slope plays a very important role, Landslide is maximum in an area where slope angle ranges from 15 to 25°to 25°-35°. But number of landslides occurrence decreases above 35°. This means that as the slope angle increases, then the shear stress in the soil or other unconsolidated material generally increase, though the landslide probability increases according to slope angle, it is not always the steep slope that are vulnerable to landslide. It can be said that undisturbed steep slope can also be more stable as compared to low angle slope which are frequently disturbed. Landuse pattern is also an important factor in this study as Landslide are more frequent in builtup areas and open forest which covers 96 landslide ie. 63.15% of the total landslide and only 0.65% landslide occur in agricultural plantation. Landslide Susceptibility map was prepared by classifying the layers into five classes of landslide susceptibility zones namely very low, low, moderate, high and very high. Then on these five classes, landslides were plotted and the landslides per unit area were generated for each sub class of the 7 causative factors used and landslide per sq.km was calculated.

1. INTRODUCTION

1.1. General Remarks

Natural Disasters such as mass movements, earthquakes, floods, cyclones, volcanic eruptions, tsunamis etc are natural hazard events that can cause extensive loss of lives and damage to the property. Almost every portion of the earth's surface experienced natural disaster in one way or the other and it can be said that no regions of the world are free from the impact of these natural hazards. Due to the increase in population and unplanned or uncontrolled development, especially in developing countries, more and more people are affected by disasters due to the expansion of their settlements in to areas that are susceptible to natural hazards. Natural disasters are often regard as inevitable but it is possible to minimize the potential risk by preparing and carry out plans to provide resilience to such disasters, and to help in rehabilitation and disaster reduction. Landslide is one of the many natural processes that alter the earth's surface. Landslide may be represent as a hazard only when it threaten mankind and causes problems to nature. Often, human activities render a slope unstable which includes change of landuse, levelling of ground for housing and formation of roads. The cutting of slope leads to slope steepening and cause slope instability.

1.2. Landslide Hazard

A landslide (including collapse, debris flow...) is one of the major natural disasters characteristic of mountainous regions. Landslides though not very devastating like earthquake, floods, cyclone in which the death toll may be a number of thousands, may lead to hundreds of deaths and billions of loss in property damage per year. With increasing unplanned urbanisation and infrastructure development particularly roads, extension of agricultural activities in areas wherein natural vegetation which was stable was existing, has severely altered the stability of slopes leading to landslide hazard. This warrants a need for studying the landslides and recognising areas which are facing the hazard. "Owing to the complex nature of landslides and due to their location inaccessible hilly places, survey for landslide investigations are difficult and expensive" (Wang, 1999). "Landslides are complex natural phenomena that are hard to model and simulate” (Pandey *et al*. 2008). Landslides takes place due to slope failures under the control of gravity and are influenced by variety of terrain factors and triggered by events such as extreme rainfall or earthquake. In India, landslides occur recurrently in Himalayan region as the region is geo-dynamically active (Saha *et al*., 2005; Chauhan *et al*., 2010) triggered by earthquake as well as heavy rain and in the Western Ghats in South India the hazard is moderate induced mainly by monsoonal precipitation. The study of landslides has received the interest of the earth scientists worldwide due to their socio-economic impacts generating large scale human tragedies, material damage and associated environmental and social hazards (*Saha et al*., 2005)

Landslide is a natural geomorphic process and human activities increase the slope instability as the natural slope is altered by developmental activities and landuse changes particularly deforestation and using the land for cultivation increase the landslide susceptibility. It involves movement of a mass of rock, debris, or earth down a slope, under the influence of gravity (Varnes, 1978; Cruden, 1991; Cruden and Varnes, 1996). Landslides can be triggered by variety of natural phenomena that causes a rapid increase in shear stress or decrease in shear strength of slope-forming materials, such as earthquakes, rainfall, rapid snow melting, storm waves and volcanic eruptions (Dai *et al*., 2002; Guzzetti *et al*., 2005). Among all, rainfall is the most common trigger. Landslides are triggered by both high intensities and short duration rainfall (Glade, 1998) as well as prolonged rainfall (Church and Miles, 1987). Landslides are one of the geological processes which causes destructions not only to roads, railway tracks, bridges, and houses but also leads to loss of life. Therefore, landslide susceptibility mapping is very much needed for identification of potential and probable landslide areas. Landslides are the result of combination of different factors, primarily involving geological, meteorological and geomorphological factors. The spatial information associated with these factors are often derived from remote sensing data, ground based information, and a number of other data sources.

Remote Sensing (RS) and Geographic Information Systems (GIS) play a crucial role in the efficient mitigation and management of disasters, the occupational framework for their monitoring, assessment, identifying gaps and recommending appropriate strategies for disaster management using these technologies. RS and GIS have become powerful tools in the prediction and estimation of natural hazards. Uses range from better monitoring of potential disasters to using GIS to create hazard analysis models that can be used to save live and property. Although, natural hazards have shown a drastic increase in magnitude and frequency in the last decades, it can be observed that there is also a remarkable increase in technical capabilities to mitigate them. Therefore, the economic damage due to natural hazards is increasing with time. These disruptions between human settlements, new urbanization, engineering contractions absorb part of the natural budget. "Hazard assessment is necessary to identify any area with degree of hazard, which well serves for land-use planning". (Arnous *et al*. 2007, 2010).

GIS is an effective tool that is used commonly used in landslide susceptibility mapping to identify in advance potential landslide-prone areas, by applying different models and approaches. The two main methods generally applied to landslide susceptibility assessment are qualitative methods, which are a direct hazard mapping techniques and quantitative methods, which are indirect mapping techniques. In qualitative methods, subjective decision rules are applied to define weights and ratings based on the expert opinion (Saha *et al*., 2002).

The GIS analysis uses intrinsic and extrinsic variables to find out landslide hazard in an area (Siddle 1991; Wu and Siddle 1995; Atkinson and Massari 1998; Dai et al. 2001). "The intrinsic variables determine the susceptibility of landslides and include bedrock geology, geomorphology, soil depth, soil type, slope gradient, slope aspect, slope convexity and concavity, elevation, engineering properties of the slope material, land use pattern, drainage patterns and so on. Similarly, the extrinsic variables tend to trigger landslides in an area of given susceptibility and may include heavy rainfall, earthquakes and volcanoes." (Dahal *et al*.,2008) Using the concept of uniformitarianism – "Past is key to the future" the landslide data is analysed and the places where slope failure has occurred is assess for their characteristics. It is probable that future landslides will occur in areas wherein similar terrain conditions exist. An area is classified into zones with different landslide susceptibility and is represented as landslide hazard Zonation maps.

Landslide hazard zonation maps (LHZM) are those in which the assessment of the probability failure is made. The LHZM hence, takes into consideration the triggering mechanism i.e., the magnitude of seismicity in earthquake induced landslides and rainfall in rain induced landslides. “The LHZM prepared for seismic – induced maps would be different from rain-induced landslides” (Chauhan et al., 2010). A landslide hazard zonation (LHZ) map separate the land surface into zones of varying degrees of stability, based on an estimated significance of causative factors in inducing instability (Anbalagan R., 1992). The other type of map is the Landslide Susceptibility maps (LSZM) in which the causative factors of landslide and areas with different degree of landslide susceptibility are takes into consideration and demarcate. Majority of the landslide zonation maps are LSZM and are more common as compared to LHZM. The scale in which the maps are prepared ranges from small to medium to large-scale maps. A large scale map is better and can be useful for administrators and planners and can also provide information which are useful and helpful for the developmental activities in a region

The present study aims to prepare a Landslide Susceptibility Map of Lunglei town and its vicinity with an aerial extent of 66.82 km^2, located in the southern part of Mizoram. Landslides have become frequent in the southern part of Mizoram during the last 2 decades due to extensive urbanisation, development of roads, changes in landuse for horticultural and agricultural activity. The landslide events in in the past 10 years have inflicted severe damage with slope failures taking place in several locations. During the years 2010 to 2019 landslides occurred in more than 200 places and were mainly in places where settlements are made and vegetables are cultivated. The settlements were more affected with houses developing cracks and loss of life. The death toll is increasing and settlements are more affected during the recent years. This indicates that people are establishing their settlements in landslide prone areas. The situation hence warrants a detailed investigation to investigate the landslides in Lunglei town and its vicinity so as to identify vulnerable zones which can be avoided for housing and other developmental activities. The landslide susceptibility zonation map of Lunglei town and its vicinity is prepared based on frequency ratio method using the landslide inventory map prepared in GIS environment. The layers for the causative factors were prepared using Survey of India Toposheets and Satellite data.

1.3. History of Landslides

All through the world, landslides have caused gigantic effect on ecology and environment, particularly in mountainous region. Quickened financial development and related formative exercises have most likely aggravated the event furthermore, repeat of slope failure. There have been certain reports of landslides in different parts of the world including Indian sub-continent. The major and noteworthy landslides events were recorded.

The problems caused by the landslides in terms of damage to property and life in different part of the earth's surface are more than other natural disaster like earthquakes, volcanic activity, tsunami etc. However, it seems that these landslide disasters are drawing lesser attention of the government, public and media as compared to other disasters taking place in different parts of the world. Every year, thousands of crores of rupees were loss due to landslide disaster in terms of social and network resources and also loss of lives. Following are the some examples of landslide events, which have taken place in the past.

Massive landslides that took place in Shimane, Japan in the year 1983 killed 107 persons, and debris flows caused by heavy rains killed 299 persons in Nagasaki (Japan) during 1982. About 500 people lost their lives due to the debris flow on July 1921 in Alma-Ata Mountain. According to GSI, "Landslides in India occur mainly during the months of July to September due to monsoon and from January to March during snowfall. Strong earthquakes also trigger landslides, particularly in regions with unstable slopes." It was estimated by GSI that the landslide prone areas in India are about 15% of the Indian landmass. In India Landslides are very common in the Himalayas especially in the North Eastern region, some parts of Jammu and Kashmir, Himachal Pradesh and Uttharakhand also experience frequent landslide every year. “Major landslides that causes loss of life and property like Malpa landslide (August, 1998), Uttarkashi landslide (September-October, 2003) and Badrinath landslide (July, 2004) are examples of this hazard” (Saha *et al*., 2005).

Landslides are also common in the Western Ghats in the southern part of India, along the steep slopes disregarding Konkan coast. Nilgiri Mountains also experienced frequent landslide, characterized by a lateritic cap, which is very prone to mass movements. Cloud bursts and flash floods accompanied by heavy rainfall is often considered as the main cause of landslides in India. Rainfall is frequently punctuated by cloud burst, which last from a length of a couple of minutes to barely few hours and leave behind a trail of devastation. Cloud bursts of intensities exceeding 1000 mm in 24 hours results in mass movements. “In the Himalayan region, it has been observed that during major landslides, high speed mud flows and avalanches occur with a speed as high as 3m to 50m per second.”(Parkash.S., 2011)

Since Mizoram is a hilly terrain landslide is the main disaster that took place in this region. “The State experienced large landslide in the year 1893, 1929 and 1965, and are recorded as *Minpui kum* (Years of large landslide). One locality in the village of Tawipui in Lunglei district is named after this, i.e. *Minpui*” (Laldinpuia, 2015). In May 1995, a massive landslide took place in Saiha and Lawngtlai where more than 8 people lost their lives and hundreds of houses were dismantled**.** One of the most devastating landslide that happened in Mizoram was Hlimen quarry slide that took place in 1992 where 66 people lost their lives. During October 2010, landslides in Siaha district caused land sinking in a big area where almost 500 houses are under threat and almost 60% area is inaccessible. During the monsoon season of 2010, Bazar veng locality of Mamit town was severely affected by landslides and subsidence endangering the lives and properties of hundreds of people. About 50 families were evacuated from their home and around 43 houses were dismantled. In 21 July 2012, the landslide from a roadside quarry at Keifang village hit a night bus where atleast 18 persons lost their lives and 17 were injured. In 11 October 2012, 3 people died due to the landslides near Dapchhuah village on Mizoram-Tripura border of Mamit district. 17 lives were lost and more than 15 buildings were shattered by the devastating landslide disaster that occurred at Laipuitlang, Aizawl on 11 May,

2013. Numerous and devastating landslides were frequently taken place in Mizoram and some of the major landslides in different districts of Mizoram recorded by the Directorate of Disaster Management and Rehabilitation Department, Govt. of Mizoram as shown in Table 1.1

Table 1.1: List of major landslides (2000-2019) in Mizoram

(Source: DM&R Department)

SL. No.	LOCATION : LOCALITY/VILLAGE	DISTRICT	YEAR
1	Ramhlun Sport Complex	Aizawl	2011
2	Laipuitlang	Aizawl	2013
3	Hunthar	Aizawl	Active/perennial
4	Rangvamual	Aizawl	2013
5	Electric Veng Hebron Ruam	Aizawl	Perennial
6	Bawngkawn	Aizawl	Perennial
7	Zemabawk	Aizawl	Perennial
8	ITI Veng	Aizawl	Perennial
9	BSUP Complex, Durtlang	Aizawl	2019
10	Edenthar	Aizawl	Perennial
11	Ngaizel (Rockfall)	Aizawl	Perennial
12	Thakthing khamphei (rockfall)	Aizawl	Perennial
13	Vaivakawn	Aizawl	Perennial
14	Armed Veng	Aizawl	2013
15	College Veng	Lunglei	2019
16	Lunglawn	Lunglei	2018
17	Mualthuam North	Lunglei	Perennial
18	Lunglei-Buarpui-Bunghmun road	Lunglei	Perennial
19	New Colony-I & II	Siaha	Perennial
20	College Veng	Siaha	Perennial
21	Tuikhuah Veng	Serchhip	Perennial
22	Below Serchhip Bazar	Serchhip	Perennial
23	Mualcheng	Serchhip	Perennial
24	Chhingchhip-Khawbel road	Serchhip	Perennial
25	Bazar Veng	Mamit	2010-2019
26	Vengthar Land subsidence	Khawzawl	Perennial
27	Ngopa	Champhai	Perennial
28	Kanan Veng	Champhai	Perennial
29	Phullen	Saitual	2015
30	Sangau	Lawngtlai	Perennial
31	Sinking portion at 474/500kmp on NH-54	Lawngtlai	Perennial
32	Chawngte-Ajasora roads	Lawngtlai	Perennial
33	M.Kawnpui-Tuichawngtlang road	Lawngtlai	Perennial

Table1.2: Data on socio-economically significant landslide in Mizoram (Parkash, S.,NIDM)

Sl. No.	Location	Month/ Year	Damages
1.	Dawrpui, Aizawl	1965	Landslide hit Aizawl Civil Hospital and a house below the hospital
2.	Ramthar Sihpui, Aizawl	1983	>300 houses damaged, road and ground subsidence, development of cracks
3.	Hlimen Slide, Aizawl	9 Aug 1992	66 killed and 17 houses destroyed
4.	Saron, Aizawl	1993	Road and buildings damaged, many people evacuated
5.	Armed Veng, Aizawl	2004	98 families vulnerable in sinking area
6.	Tuikual, Aizawl	13 Sept 2010	1 killed
7.	Ngopa, Mizoram	1993	55 families and 45 buildings affected by landslides
8.	Aizawl, Mizoram	June, 1993	4 deaths
9.	Aizawl, Mizoram	May, 1995	25 deaths and roads damaged
10.	Lawngtlai-III, Mizoram	1995	Sinking area affects NH-54 and numerous houses
11.	Kolasib distt, Mizoram	12 Sept. 2007	75000 acres of cultivated land
12.	Bazar veng, Mamit	2010	44 houses dismantled including Presbyterian church and graveyard
13.	Mamit, Mizoram	6 Aug 2010	3 houses damaged, 10 houses and shops declared unsafe
14.	Laipuitlang, Aizawl	15 May 2013	17 deaths, 15 houses collapsed.
15.	Aizawl, Mizoram	August 2015	3 houses and 70 graves in two cemeteries damaged
16.	Lunglawn, Lunglei	4 June 2018	1 house destroyed and 10 deaths and 4 injured.
17.	BSUP complex, Durtlang, aizawl	2 July 2019	3 deaths and 9 injured

1.4. Types of Landslides:

"The various types of landslides can be differentiated by the kinds of material involved and the mode of movement. Some common types of landslides are earth flows, debris flows, debris avalanche, mudflows, rockslide, slumps, rockfalls, liquefactions, creeps, etc. The classification system of landslides given by Varnes (1978) based on these parameters is shown in the Table 1.3. Landslides are also classified based on the volume of material dislodged. Table 1.4 gives the classification of landslides based on the volume.

Table 1.3: Types of landslides.

(Abbreviated version of Varne's classification of slope movements (Varnes, 1978)

Type of Movement		Type of Material		
		Bedrock	Engineering Soils	
			Predominantly Coarse	Predominantly Fine
	FALLS	Rock fall	Debris fall	Earth fall
	TOPPLES	Rock topple	Debris slide	Earth slide
SLIDES	ROTATIONAL	Rock slide	Debris slide	Earth slide
	TRANSLATIONAL			
	LATERAL SPREADS	Rock spread	Debris spread	Earth spread
	FLOWS	Rock flow (deep creep)	Debris flow	Earth flow
			(soil creep)	
	COMPLEX	Combination of two or more principal types of movement		

Table 1.4: Classification of Landslides based on the volume of sliding material (Fell, 1994)

Magnitude	Description	Volume m^3
7	Extremely large	>5,000,000
6	Very large	1,000,000 to 5,000,000
5	Medium large	250,000 to 1,000,000
4	Medium	50,000 to 250,000
3	Small	5,000 to 50,000
2	Very small	500 to 5,000
1	Extremely small	<500

1.4.1. SLIDES:

The two major types of slides are rotational slides and translational slides.

1.4.1.1 Rotational slide:

Rotational slides are the slide in which the surface of rupture is concave and curved upward and the movement of the slide is roughly rotational about an axis parallel to the ground surface and transverse across the slide. If the rupture surface is circular the mass which are displaced move along the surface with less internal deformation (fig. 1.2 A).

1.4.1.2. Translational slide:

In this type of slide, the landslide mass moves along a roughly planar surface with little rotation or backward tilting (fig. 1.2 B). A block slide is a translational slide in which the moving mass consists of a single unit or a few closely related units that move down slope as a relatively coherent mass (fig. 1.2 C).

1.4.2. Debris slides:

A debris slide is a rapidly moving coherent mass of debris.

1.4.2.1. Rockslides:

Rockslides are, as the term suggests, the rapid sliding of a mass of bed rock along an inclined surface of weakness. Once sliding begins, a rock slap usually breaks up into rubble. Like rockfalls, rockslides can be caused by undercutting at the base of the slope from erosion or construction.

Some rockslides travel only a few meters before halting at the base of a slope. In country with high relief, however, a rockslide may travel hundreds or thousands of meters before reaching a valley floor. If movement becomes very rapid, the rockslide may break up and become a rock avalanche. A rock avalanche is a very rapidly moving, turbulent mass of broken-up bed rock. Movement in a rock avalanche is flowage on a grand scale.

Some geologists have suggested that in very rapidly moving rock avalanches, air trapped under the rock mass creates an air cushion that reduces friction. This could explain why some landslides reach speeds of several hundred kilometres per hour. But other geologists have contended that the rock mass is too turbulent to permit such an air cushion to form. Ultimately, a rockslide or rock avalanche comes to rest as the terrain becomes less steep. Sometimes the mass of rock fills the bottom of a valley and creates a natural dam. If the rock mass suddenly enters a lake or bay, it can create huge waves that destroy lives and property far beyond the area of the original landslide.

1.4.3. Falls:

Falls are abrupt movements of masses of geologic materials, such as rocks and boulders that become detached from steep slopes or cliffs (fig. 1.2 D). Separation occurs along discontinuities such as fractures, joints, and bedding planes and movement occurs by free-fall, bouncing, and rolling. Falls are strongly influenced by gravity, mechanical weathering, and the presence of interstitial water.

1.4.3.1. Rockfall:

In the movement call rockfall, rock falls freely or bounces down a cliff. When a steep slope or cliff is being undercut, as by a river or wave erosion or highway construction, large blocks of rock tend to break off along cracks in the bedrock or along planes of weakness such as bedding planes. Blocks of rock commonly break off through frost wedging (a type of mechanical weathering). Most cliffs have an apron of fallen rock at their bases that are the result of rockfall. An accumulating of broken rock(from rockfalls) at the base of a cliff is called talus.

1.4.4. Topples:

Toppling failures are distinguished by the forward rotation of a unit or units about some pivotal point, below or low in the unit, under the actions of gravity and forces exerted by adjacent units or by fluids in cracks (fig. 1.2 E)

1.4.5. Flows: There are different types of flows that differ from one another viz. creep, earthflow, mudflow, debris flow, debris avalanche etc.

1.4.5.1. Creep:

Creep is very slow, continuous, downslope movement of soil or unconsolidated debris (fig. 1.2 I). The rate of movement of soil is usually less than a centimetre per year and can be detected only by observations taken over months or years. When conditions are right, creep can take place along nearly horizontal slopes.

Two factors that contribute significantly to creep are water in the soil and daily cycles of freezing and thawing. Although creep does take place in year-round warm climates, the process is more active where the soil freezes and thaws during part of the year. During the winter in regions like north-eastern United States , the temperature may rise above and fall below freezing once a day or several times daily. When there is moisture in the soil, each freeze-thaw cycle moves soil particles a minute amount downhill. Creep can take place at gentle slopes and is a slow process. In tropical regions, undermining by streams down slope may cause creep. Creep cannot be observed as it is a very slow process and evidences for creep are slanting poles and non-heliotropic nature of tree and tilted poles.

1.4.5.2. Earthflow:

In an earth flow, debris moves downslope as a viscous fluid; the process can be slow or rapid (Fig. 1.2 H). Earth flows usually occur on hillsides that have a thick cover of debris, often after heavy rains have saturated the soil. Typically, the flowing mass remains covered by a blanket of vegetation, with a scarp (steep cut) developing where the moving debris has pulled away from the upper slope, which remains stationary.

An earth flow can be only a flow, with soil movement roughly parallel to the slope. Most earth flows, however, involve both slip and flow. In an earthflow the upper part of the earthflow slumps downward as a relatively coherent block, shoving the lower part outward and causing the debris to flow downhill. Meanwhile, a hummocky lobe forms at the toe or front of the earthflow. An earth can be active over a period of hours, days, or months; in some earth flows intermittent slow movement continues for years.

Human can trigger earth flows by adding too much water to soil from septic tank systems or by overwatering lawns. Earth flows, like other kinds of landslides, can be trigger by undercutting at the base of a slope. The undercutting can be caused by waves breaking along shorelines or streams eroding and steepening the base of a slope.

1.4.5.3. Mudflow:

A mudflow is a flowing mixture of debris and water usually moving down a channel. It can be visualised as a stream with the consistency of a thick milkshake. Usually after a heavy rainfall slurry of soil and water forms and begin moving down a slope. Most mudflows quickly become channelled into valleys. They then move down valley like a stream except that, because of the heavy load of debris, they are more viscous. Mud moves more slowly than a stream but because of its high viscosity can transport boulders, automobiles, and even locomotives. Houses in the path of a mudflow will be filled with mud, if not broken apart or carried away.

Mudflows are more likely to occur in arid regions than in wet climates where a dense cover of vegetation protects soil and debris. A hillside in a desert environment where it had not rained for many years, may be covered with a blanket of loose material. With sparse desert vegetation offering like protection, a sudden thunderstorm with drenching rain can rapidly saturate the loose debris and create a mudflow in minutes. Lack of vegetation can be the cause of mudflow in other situations. Mudflows frequently occur on young volcanoes that are littered with ash. Heavy flows or rapid flow can be triggered by renewed volcanic activity on a glaciated volcano. Mudflows also occurred after forest fires have destroyed slope vegetation that normally anchors soil in place. Burned-over slopes are extremely vulnerable to mudflow if heavy rains fall before the vegetation is restored

1.4.5.4. Debris flows:

A debris flow is a free-falling mass of debris. Rock fragments, mud, and water flow down the slope as thick viscous fluid. Debris flows, may begin as slumps and continue as flows. Movement may be as slow as that of freshly powered concrete or as rapid as that of a river. When the mass of the debris increases and travels with tremendous force, it is called as debris avalanche.

1.4.5.5. Debris Avalanche:

A debris avalanche is debris moving very rapidly and turbulently downslope. (Fig. 1.2 G) It is a type of slide characterized by the chaotic movement of rocks, soil and debris mixed with water or ice (or both). They are usually triggered by the saturation of thickly vegetated slopes which results in an incoherent mixture of broken timber, smaller vegetation and other debris. Debris avalanches differ from debris slides because their movement is much more rapid. This is usually a cause of lower cohesion or higher water content and commonly steeper slopes.

1.4.5.6. Quick clays:

Quick clays are fine silt and clay particles saturated with water, when disturbed by a sudden shock, lose their cohesiveness and flow like a liquid.

1.4.6. Solifluction and permafrost:

One variety of earthflow is usually associated with colder climates. Solifluction is the flow of water-saturated debris over impermeable material. Because the impermeable material beneath the debris prevents water from draining freely, the debris between the vegetation cover and the impermeable material becomes saturated. Even a gentle slope is susceptible to movement under these conditions.

The impermeable material beneath the saturated soil can be either impenetrable bed rock or, as is more common, permafrost, ground that remains frozen for many years. Most solifluction takes place in areas of permanently frozen ground, such as in Alaska and northern Canada. Permafrost occurs at depths ranging from a few centimetres to a few meters beneath the surface. The ice in permafrosts acts as a cementing agent for the debris. When all the pores are filled with ice, the ground becomes a concrete like mass. Above the permafrost is a zone that, if the debris is saturated, is frozen during the winter and distinguishable from the underlying permafrost. When this zone thaws during the summer, the water, along with water from rain and runoff, cannot seep downward through the permafrost, and so the slopes become susceptible to solifluction. Since solifluction movement is not rapid enough to break up the overlying vegetation cover into blocks, the water-saturated debris flows downslope, pulling vegetation along with it and forming a wrinkled surface. Gradually the debris collects at the base of the slope, where the vegetated surface bulges into a hummocky lobe.

1.4.7. LATERAL SPREADS:

Lateral spreads are distinctive because they usually occur on very gentle slopes or flat terrain (Fig. 1.2 J). The dominant mode of movement is lateral extension accompanied by shear or tensile fractures. The failure is caused by liquefaction, the process whereby saturated, loose, cohesionless sediments (usually sands and silts) are transformed from a solid into a liquefied state. Failure is usually triggered by rapid ground motion, such as that experienced during an earthquake, but can also be artificially induced. When coherent material, either bedrock or soil, rests on materials that liquefy, the upper units may undergo fracturing and extension and may then subside, translate, rotate, disintegrate, or liquefy and flow. Lateral spreading in fine-grained materials on shallow slopes is usually progressive. The failure starts suddenly in a small area and spreads rapidly. Often the initial failure is a slump, but in some materials movement occurs for no apparent reason. Combination of two or more of the above types is known as a complex landslide.

1.4.8. SLUMPS: The resistant rocks overlying the weaker rock layers, as the erosion of the bottom weak layers attain unstable and slumps. Such slump blocks can be as much as several thousand cubic meters. They matter seconds or gradually slip over a period of several weeks.

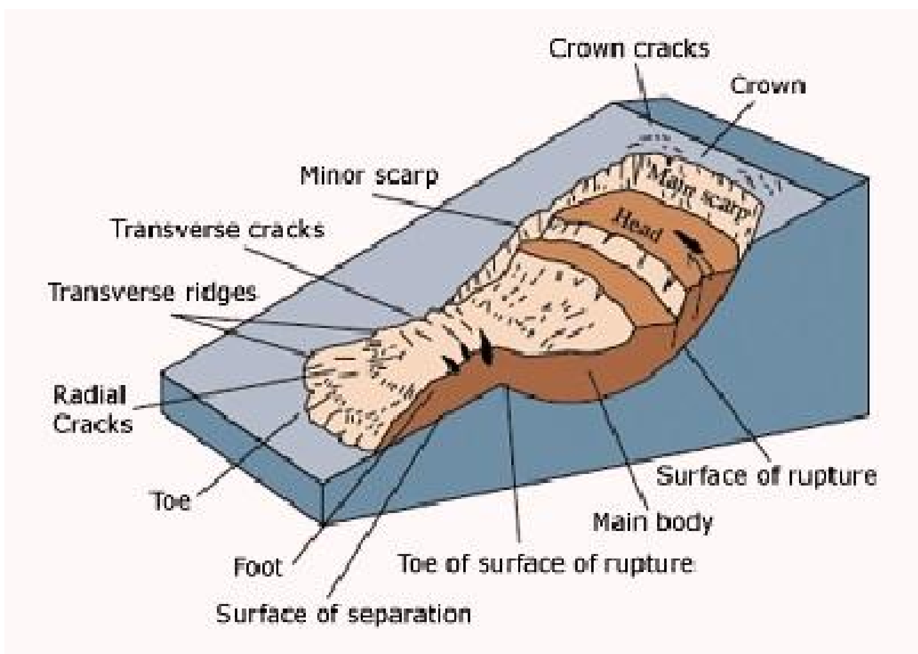


Fig. 1.1: An idealized slump-earth flow (source : USGS)

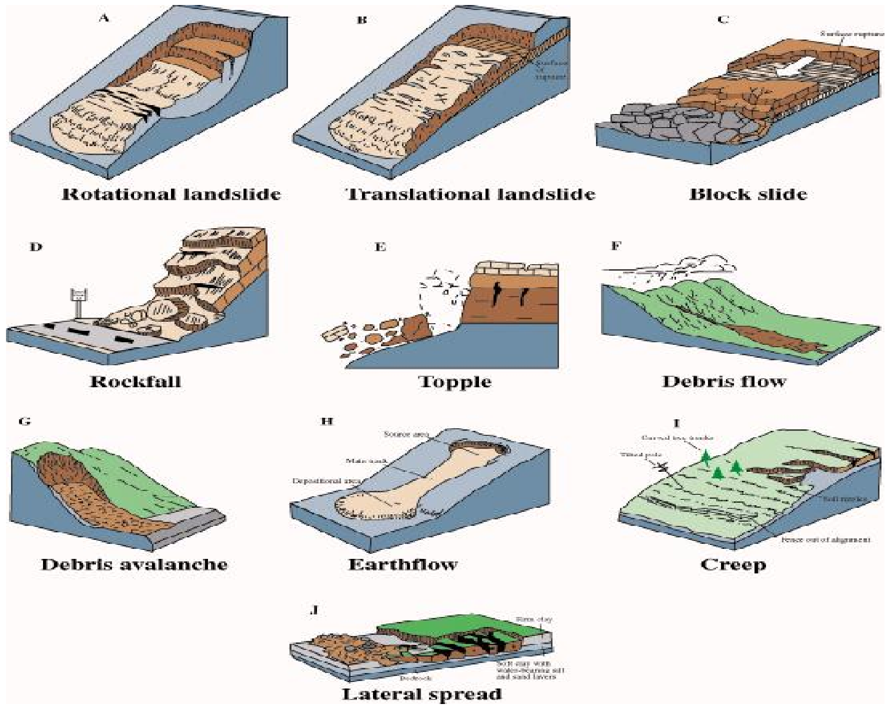


Fig. 1.2: Major Types of Landslide (source: USGS)

1.5. MAIN CAUSES OF LANDSLIDES

1.5.1. Geological causes: There are numerous geological factors that causes landslides on earth. Weak or sensitive materials, sheared, jointed or fissured materials and adversely oriented discontinuity such as bedding, schistosity, fault, unconformity are the most common geological structures that causes landslides. Moreover, contrast in permeability and stiffness of materials and sharp fluctuations in groundwater level are also common causes. Earthquakes are also important geological factors that trigger landslides as it creates stresses that results in the falling of weak slopes.

1.5.2. Morphological causes: Tectonic activities and fluvial, wave, or glacial erosion of slope toe or lateral margins, thawing and freeze-and-thaw weathering can be the reason for the occurrence of landslides. Subterranean erosion (solution, piping), deposition loading slope or its crest and removal of vegetation by fire and drought and slope angle are the most common morphological causes of landslides.

1.5.3. Physical causes: Physical factors like intense rainfall, rapid snow melt, prolonged precipitation, rapid drawdown, thawing, shrink-swell and ground water changes can lead to the occurrence of landslides.

1.5.4. Anthropogenic causes : Excavation of slope or its toe, loading of slope or its crest, drawdown of reservoirs, deforestation, mining, artificial vibration, improper drainage system and water leakage from utilities are the most common triggering factors of landslides.

Although there are multiple types of causes of landslides, the three that cause most of the damaging landslides around the world are these:

1.6. Landslides and Water

Slope saturation by water is a primary cause of landslides. This effect can occur in the form of intense rainfall, snowmelt, changes in ground-water levels, and water-level changes along coastlines, earth dams, and the banks of lakes, reservoirs, canals, and rivers.

Landsliding and flooding are closely allied because both are related to precipitation, runoff, and the saturation of ground by water. In addition, debris flows and mudflows usually occur in small, steep stream channels and often are mistaken for floods; in fact, these two events often occur simultaneously in the same area. Landslides can cause flooding by forming landslide dams that block valleys and stream channels, allowing large amounts of water to back up. This causes backwater flooding and, if the dam fails, subsequent downstream flooding. Also, solid landslide debris can "bulk" or add volume and density to otherwise normal stream flow or cause channel blockages and diversions creating flood conditions or localized erosion. Landslides can also cause overtopping of reservoirs and/or reduced capacity of reservoirs to store water.

1.7. Landslides and Seismic Activity

Many mountainous areas that are vulnerable to landslides have also experienced at least moderate rates of earthquake occurrence in recorded times. The occurrence of earthquakes in steep landslide-prone areas greatly increases the likelihood that landslides will occur, due to ground shaking alone or shaking-caused dilation of soil materials, which allows rapid infiltration of water. The 1964 Great Alaska Earthquake caused widespread landsliding and other ground failure, which caused most of the monetary loss due to the earthquake. Other areas of the United States, such as California and the Puget Sound region in Washington, have experienced slides, lateral spreading, and other types of ground failure due to moderate to large earthquakes. Widespread rockfalls also are caused by loosening of rocks as a result of ground shaking.

1.8. Landslides and Volcanic Activity

Landslides due to volcanic activity are some of the most devastating types. Volcanic lava may melt snow at a rapid rate, causing a deluge of rock, soil, ash, and water that accelerates rapidly on the steep slopes of volcanoes, devastating anything in its path. These volcanic debris flows (also known as lahars) reach great distances, once they leave the flanks of the volcano, and can damage structures in flat areas surrounding the volcanoes.

1.9. LANDSLIDE REMEDIAL MEASURES:

1.9.1. MODIFICATION OF SLOPE GEOMETRY

- Removing material from the area driving the landslide (with possible substitution by lightweight fill)
- Adding material to the area maintaining stability (counterweight berm or fill)
- Reducing general slope angle

1.9.2. DRAINAGE

- Surface drains to divert water from flowing onto the slide area (collecting ditches and pipes)
- Shallow or deep trench drains filled with free-draining geomaterials (coarse granular fills and geosynthetics)

- Buttress counterforts of coarse-grained materials (hydrological effect)
- Vertical (small diameter) boreholes with pumping or self draining
- Vertical (large diameter) wells with gravity draining
- Sub horizontal or sub vertical boreholes
- Drainage tunnels, galleries or adits
- Vacuum dewatering
- Drainage by siphoning
- Electro-osmotic dewatering
- Vegetation planting (hydrological effect)

1.9.3. RETAINING STRUCTURES

- Gravity retaining walls
- Crib-block walls
- Gabion walls
- Passive piles, piers and caissons
- Cast-in situ reinforced concrete walls
- Reinforced earth retaining structures with strip/ sheet - polymer/metallic reinforcement elements
- Buttress counterforts of coarse-grained material (mechanical effect)
- Retention nets for rock slope faces
- Rockfall attenuation or stopping systems (rocktrap ditches, benches,fences and walls)
- Protective rock/concrete blocks against erosion

1.9.4. INTERNAL SLOPE REINFORCEMENT

- Rock bolts
- Micropiles
- Soil nailing
- Anchors
- Grouting
- Stone or lime/cement columns
- Heat treatment
- Freezing
- Electroosmotic anchors
- Vegetation planting (root strength mechanical effect)” (USGS, 2004)

1.10. Scope of the study

The study area is frequently subjected to landslides especially during monsoon. Though several landslide incidences have been recorded almost every year resulting in loss of lives and properties, but works on landslides studies are still very inadequate in this region. Moreover, landslide studies by statistical approach (frequency ratio method) using Geographic Information System has never been taken up in the proposed study areas. This study aims to prepare a Landslide Susceptibility Map of Lunglei town and its vicinity using GIS. Landslides occurred more frequently and become more hazardous in and around Lunglei town during the last two decades. This could be due to an extensive urbanization, development of roads, changes in land use for horticultural and agricultural activities. Identification, mapping and monitoring of landslide susceptible zones and safer/stable zones using GIS would help in the mitigation of landslides as well as in rehabilitation of the victims. The result of the proposed study can also be used as basic information by decision makers and for slope management and land use planning.

1.11. Objectives

1. To prepare landslide inventory map of the study area
2. To prepare thematic maps for different causative factors of landslide like slope, lithology, structure, drainage, and land use land cover maps
3. To prepare Landslide Susceptibility Zonation Map at 1: 50,000 scale of the study area using GIS and Frequency Ratio Method.

1.12. REVIEW OF LITERATURE

A large amount of research on landslide studies has been carried out over the last 30 years as the consequence of an urgent demand for slope instability hazard mapping. Overviews of the various slope instability hazard zonation techniques can be found in Brabb (1984), Guzzetti *et al*., (1999), Hansen (1984), and Varnes (1984).

Many methods and techniques have been proposed to evaluate landslide prone area using GIS and/or remote sensing (Aleotti and Chowdhury 1999; Carrara *et al*. 1999; Guzzetti *et al*. 1999; Lan *et al*. 2004; Lee and Min 2001; Mantovani *et al*. 1996; Nichol and Wong 2005; Odajima *et al*. 1998; Sarkar and Kanungo 2004; Van Westen 2000; Van Westen 1993) and many of these studies have applied probabilistic methods (Guzzetti *et al*. 2005; J.L.Zêzere *et al*. 2004; Lee *et al*. 2004; Luzi *et al*. 2000; Zhou *et al*. 2003). Probabilistic approaches are based on the observed relationships between each factor and the distribution of landslides.

Varnes D. J. (1984) pioneering work on the landslide hazard zonation is the forerunner for the modern attempts for landslide hazard mitigation and forms the fundamental basis of several investigations. According to him predicting aerial limits of ‘‘Landslide hazard’’ is a particular case of natural hazard defined as ‘‘the probability of occurrence within a specified period of time and within a given area of a potentially damaging phenomenon’.

Lee and Talib (2004) used geographic information system (GIS) and remote sensing data to assess the susceptibility of landslides and the effect of landslide-related factors at Penang in Malaysia. They applied the frequency ratio method for their studies and the factors used for landslide occurrence were: topographic slope, topographic curvature, topographic aspect and distance from drainage, lithology and distance from lineament were taken from the geological database and Landsat Thematic Mapper (TM) satellite images was used to extract land use; and the vegetation index value from SPOT HRV (High-Resolution Visible) satellite images.

Lee and Pradhan (2007) also assessed the landslide hazards at Selangor area, Malaysia, using Geographic Information System (GIS) and Remote Sensing. Areas prone to Landslide prone were studied and mapped using the landslide-causing factors by frequency ratio and logistic regression models. The results of their analysis were confirmed by the landslide location data and compared with probability model. The comparison results showed that the frequency ratio model (accuracy is 93.04%) is better in prediction than logistic regression model (accuracy is 90.34%).

Brabb, E.E. (1984) made an innovative approach to landslide hazard mapping introducing semi quantitative method consisting of a bivariate analysis of landslide area, percentages in slope angle intervals, expressed by relative susceptibility numbers, from which a susceptibility zonation was obtained.

Carrara *et al.* (1991, 1995) also used GIS technology for landslide hazard mapping. The “slope units” concept was proposed by Carrara *et al.* (1991, 1995) for the improvement of landslide hazard maps.

Gupta *et al.* (1993) studied the slope stability of Upper Sutlej valley in Himachal Pradesh and prepared a landslide hazard zonation map.

Jaganathan and Chauniyal (2000) prepared Landslide Hazard Zonation for a 64 km^2 Kelani area, located in the fringe of Garhwal (Pauri district) and Kumaun (Almora District) using remote sensing and GIS techniques with evidential weighted approach based on twelve geo-environmental parameters. They used aerial photo-interpretation and field survey for Geomorphological and landuse studies and to demarcate the landslides. But, they did not take account of the smaller slides along road cuts, canals and settlements in the landslides inventory. The hazard map with five group of hazard zones viz., very low, low, moderate, high and very high is prepared based on the weighted sum of all classes and all geo-environmental parameters.

Ayalew *et al*. (2004) calculated landslide susceptibility mapping using GIS-based weighted linear combination, the case in Tsugawa area of Agano River, Niigata Prefecture, Japan. They mapped the plotted 791 landslide events in the 407 km^2 area at a scale of 1:20,000 with a pixel resolution of 10 × 10 m. Followed by layering and the assigned six weighted factors using the linear combination method, a GIS model was developed which consider both landslide frequencies as well as expert knowledge of the factors that influence slope instability in the area.

Sarkar and Kunungo (2004) studied part of Darjeeling Himalaya and made an integrated approach for landslide susceptibility using remote sensing and GIS. Since, the landslide data set is small, they opine that statistical approach will give incorrect result and hence, developed a rating system with which they produced a landslide susceptibility zonation map.

Sarkar and Gupta (2005) have prepared Landslide Hazard Zonation maps for Srinagar-Rudraprayag area in Garhwal Himalaya in 1:50000 scale using two techniques viz., (1) Subjective Regional Zonation and (SRZ) and (2) Objective Regional Zonation (ORZ). Sarkar and Anbalagan (2008) made a macro-level landslide hazard zonation for the area south of Alaknanda River covering 80 km^2. They first prepared a facet map of the study area with natural topographic boundaries like hill ridges, spurs, streams and major slope breaks. Their study shows that the preparations of Macro Hazard Zonation (MHZ) Map for the area using the same techniques provided a better assessment of landslide potential zones and give more information.

Ghafoori *et al.* (2006) prepared a landslide hazard Zonation map in Bormahan basin, northern Ian depicting the division of the land surface into zones of varying degrees of stability based on estimated significance factors which are important in a slope area. They determined the effective parameters for landslide based on a quantitative approach by calculating the ratio of landslide percentage in a geological unit and the unit coverage percentage in the slope area. According to them there are different methods of landslide hazard zonation with some advantages and disadvantages. They suggest that the Relative Effect Method (R.E.M), which is a statistical methods using GIS software for landslide hazard zonation, which determines the relative effect (RE) of each unit, such as surface geology, slope morphometry, climatic conditions, land use and land cover by calculating the ratio of the unit portion in coverage and landslide is more suitable.

Mathew *et al.* (2009) attempted landslide susceptibility mapping in part of Garhwal Lesser Himalaya lying close to the Main Boundary Thrust using binary logistic regression analysis and validated it. They recognised 31 predictor variable classes of which 13 were used as they had statistically significant estimated coefficients. They validated the predictive logistic regression model by receiver operating characteristic curve analysis and found that it gives 91.7% accuracy for the model.

Kumar (2007) had carried out macro-level LHZ of area around Lunglei town on 1: 25,000 scale. He assessed and assigned LHEF values with 14 points rating scheme from ten geo-environmental parameters like slope morphometry, relative relief, land use and land cover, lithology, structure, hydrogeological condition, rainfall, landslide incidence and slope erosion. He also observed that the main causes of landslides in his study area are excavation and removal of toe support along road side, steep slope, soft and friable shale and nala erosion.

Balamurugan, G. *et al* (2016) carried out landslide susceptibility mapping using frequency ratio and fuzzy gamma operator models with the help of geomatics techniques in part of NH-39, Manipur, India. They prepared the landslide susceptibility map using landslide inventory data and used nine landslide causative factors, i.e. lithology, land use and land cover, geomorphology, drainage density, lineament density, slope gradient, slope aspect, curvature, and elevation.

Hawas Khan *et al* (2018) had done Landslide susceptibility assessment for Northern Pakistan using frequency ratio method in GIS. They used SPOT-5 satellite image to develop a landslide inventory map. They also prepared thematic layers for landslide causative factors such as slope and aspect, geology, landcover, distances from fault, road and streams to evaluate their influence on the spatial distribution of landslides. The study shows that the distance to road and slope gradient has the most significant influence on the spatial occurence of landslides, which was followed by the geology of the area.

Silalahi, F.E.S., Pamela, Arifianti, Y. *et al.* (2019) implemented GIS mapping and analysis using a Frequency Ratio Model to assess the contribution of conditioning factors to landslides in order to prepare a landslide susceptibility map of the Bogor, West Java in Indonesia. They prepared digital elevation model for the study area and also 5 thematic maps like soil, rainfall, land cover, and geology map were generated to examine landslide conditioning factors. The relationship between landslides and causative factors were statistically evaluated with Frequency ratio analysis. The Landslide susceptibility map prepared thus shows that lithology, soil, and land cover are the most important factors that triggered the landslides in this study area.

Tiwari *et al* (1996) prepared Landslide hazard zonation map for the first time for the road section between Hrangchalkawn and Rotlang in the Lunglei District of Mizoram. The road section is 41km long. Landslide hazard evaluation factors (LHEF) rating scheme given by Anbalagan (1992) was followed for this study. They demarcated facets and prepared thematic maps for the study area and produce estimation of LHEF rating and total estimated hazard (TEHD) was worked out. The area is classified into five zones of landslide hazard; namely, very low hazard, low hazard, moderate hazard, high hazard and very high hazard zones based on the ranges of TEHD. Moderate and high hazards zones form the maximum area of the study area.

Lawmkima (2010) studied landslide hazard in Aizawl city using GIS environment with detailed investigations of selected landslides such as Bawngkawn, Sairang and South Hlimen; he also prepared landslide disaster management plan.

Laldinpuia *et al.* (2011) had carried out geotechnical studies of Ramhlun Vengthar landslide, Aizawl. They stated that the main causes of Ramhlun Vengthar landslide are steepness of the slope, poor drainage system, toe erosion and heavy rainfall. Such factors affected reduction of shearing strength, which influenced loss of houses and vulnerable area to another landslide.

Laltlankima and F. Lalbiakmawia (2016) investigated the Landslide Hazard Zones along the highway between Aizawl city and Lengpui airport of Mizoram using Remote Sensing and Geographic Information System (GIS) technique. They prepared five thematic layers and these thematic layers were ranked and weighted based on their importance in landslide occurence. Each class within a thematic layer was rated from 1 to 10 as attribute information using GIS. They prepared Landslide Hazard Zonation Map for the study area and classified them into five zones viz.,very high, high, moderate, low and very low.

Lallianthanga R.K. and Laltanpuia Z.D. (2013) also carried out Landslide Hazard Zonation mapping of Lunglei town using high resolution satellite data in GIS environment. They prepared thematic layers for lithology, geological structures, slope morphometry, geomorphology and land use/land cover using quickbirdsatelite imagery and IRS-P5 stereo-paired Cartosat-I data and they classified the area into five zones.

Laldinpuia *et al.* (2013) reported the 11th May 2013 Laipuitlang rockslide disaster of Aizawl. This rockslide claims 17 lives and 8 persons were rescued alive. This tragic disaster improved the State disaster management system. They observed that the main causes of rockslide are a combination of soft and high porous rock bedding, steep slope, heavy rainfall, anthropogenic devastation of the rock bed and overweight construction.

Lallianthanga & Lalbiakmawia (2013A & 2013B) prepared Landslide Hazard Zonation of Aizawl District, Mizoram, India using Remote Sensing and GIS techniques (ARCINFO v9.3) using the data of Cartosat-I and IRS (P6) LISS III generated on a scale of 1:5,000. The map having five hazard zones *viz.* very high hazard zone (10.51%), high hazard zone (23.49%), moderate hazard zone (42.08%), low hazard zone (21.12%) and very low hazard zone (2.4%). They also published Landslide Hazard Zonations' of Lunglei, Kolasib and Lawngtlai towns respectively.

Lallianthanga & Lalbiakmawia (2013C) carried out a micro-level Landslide Hazard Zonation of Aizawl city using Quick bird satellite data having spatial resolution of 0.8m and IRS-P5 stereo-paired Cartosat-I data having spatial resolution of 2.5m. They generated a map of 1:5,000 scale after five parameters like slope morphometry, landuse/ land cover, lithology, geomorphology and geological structures. The LHZ was categorised into 'Very High' (1.30%), 'High' (20.75%), 'Moderate' (44.19%), 'Low'(27.82%) and 'Very Low' (5.91%) hazard zones.

Laldinpuia *et al.* (2014) studied 11th May, 2013 Laipuitlang rockslide, employed Schmidt Hammer (N/NR type) for measuring rebound value strength of rock and degree of weathering. They observed the main rock type of the slide area as highly decomposed classified as Grade-IV in rock material decomposition grades and the rock strength was moderately weak. They also concluded that further research on laboratory testing of rocks and more rigorous slope stability analyses are needed.

1.13. STUDY AREA

The study area covers the entire Lunglei town and its vicinity. It falls within the Survey of India Toposheet No. 84 B/9 and 84 B/13. Geographically, it is situated between the co-ordinates of $92^{\circ}42'45''$ E - $92^{\circ}50'05''$ E longitudes and $22^{\circ}48'18''$ N - $22^{\circ}56'55''$ N latitudes. and covers an area of 66.82 sq.km**.** The location map of the study area is shown in Fig.1.3. It is accessible by National highway NH54 and is 165km from the city of Aizawl.

Lunglei town is the second largest town in Mizoram and the total population is 57,011 according to Census 2011. Lunglei town has been experiencing a fast growth in urbanization. With increasing urbanization the town has undergone various developmental activities without sufficient consideration of the existing slopes instabilities. This coupled with heavy rainfall, soft nature of the sediments, topography and complex structural disposition leads to manifold increase in the incidence of landslides in the region. Though these movements cannot be stopped from occurring, their effect can be minimized through suitable mitigation measures for reducing their frequency and severity.

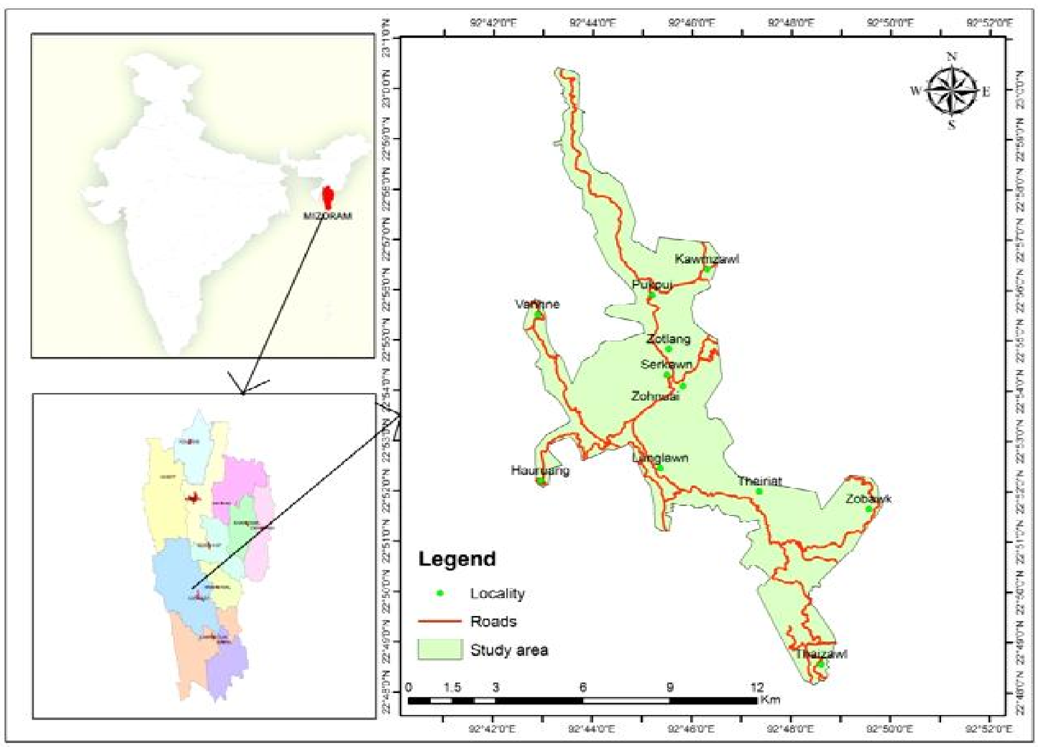


Fig. 1.3. Location map of the study area

1.13.1. Climate and rainfall of Lunglei District:

The district has a pleasant climate, which is not very cold in winter and generally cool in summer. In winter the temperature varies from 5°C to 24°C while in summer it is between 19°C to 32°C. There is no snowfall in the district, though eastern parts of the districts often experienced frost. The western part of the district is lower in elevation as compared to the eastern part and thus it experiences a slight warmer climate than the eastern part. The temperature starts to fall down sharply from the month of November and it is reduce in December and January. January is the coldest month with the mean daily maximum temperature at 24°C and the mean daily minimum temperature of 5 to 6 ° C.

The district receives sufficient amount of rainfall which is under the direct influence of the south west Monsoon. Monsoon starts from the month of May to September and maximum rainfall is received during the month of July. 80% of the total rainfall occurs between May and September and only remaining 20% occurs during the other months. "This coincidence of the occurrence of south west monsoon with the summer makes the climate favourable for inhabitants of the district since the temperature is kept down to a considerable extent by the usual rains. Normally, June and July are the rainy months while December and January are the dry months". (KVK Lunglei). The district is drained by several important rivers like Khawthlangtuipui, Mat, Tuichawng, Tuichang Tlawng and Tuipui rivers. River Tlawng is the longest river in Mizoram originated from Lunglei which is about 8km east of Lunglei town at the height of about 1395 metres. The average rainfall for Lunglei District is about 2572 mm per annum and during summer precipitation is high.

2. GEOLOGICAL SETTING

2.1. INTRODUCTION

Knowledge on the geological settings and a true understanding of the tectonic evolution of a region are crucial steps of any geological investigation for a selected area within that region. Provenance, denundation processes and plate mechanism studies provide useful clues in unravelling the various geomorphic and tectonic processes which resulted in the present geologic set up. The type of rocks, their formation and the degree of deformation brought about by tectonic forces, aided by physical forces provides much needed knowledge to comprehend the stability of the area in terms of mass wasting activities. This information also helps us to better comprehend past activities and the degree of stability and risk of present and future landslides. So, to truly understand the fastness of an area, in depth knowledge on the regional geological settings is necessary.

The present area of interest is situated in the Southern part of one of the North-south trending anticline formed as a result of the Indo-Myanmar oblique collision constituting the Southern extend of the Indo Burma Range (IBR). The main geologic features and processes responsible for its existence are the Himalayan Ranges, the Bengal Basin, Shillong Plateau, Surma Basin, and Indo-Burma Ranges (IBR).

2.2. THE HIMALAYAN RANGES

The Himalayan mountain range was formed due to the collision of Indian and Eurasian plates which resulted in closure of the Tethys Sea. These are the most majestic inland mountain range which forms the main geological framework of the area and stretches over a length of 2500km trending east-west with a width of about 300kms in north-south direction.The mountain range consists of litho-tectonic zones, separated by thrust and normal faults (Gansser, 1964). The Sub-Himalayan lithotectonic zone consists of the foreland basin sediments eroded from the still rising orogen in its northern front (Parkash et al., 1980). The sediment sequence of the Himalayan foreland basin provides detail knowledge on the chronology and style of evolution of the Himalaya (Sinclair, 1997; DeCelles, et al., 1998; Burbank et al 1996; Najman 2006).

The sediment depositional pattern from marine to continental transition makes the most characteristic transformation of the foreland basin. These transitions are variously reported throughout the length of the Himalayan foreland basin West to East including the Hazara-Kashmir syntaxis in Pakistan representing the shallow marine facies of Patala Formation overlain by continental facies of Muree Formation. Similar pattern is reported in Kohat and Potwar plateaus (Critelli and Grazanti, 1994, Najman et al., 2001). In Nepal early Mid Eocene shallow marine facies of the Bainskati formation are unconformably overlain by Dumri series of alluvial sediments (DeCelles et al. 1998). Several excellent sections are available in the Lesser Himalayas of India and Pakistan where transition from a neritic to shallow marine environment changed to intertidal, lagoonal and finally completely fluvial environments during Subathu to Dagshai (Sahni and Kumar, 1974). In the Jammu region the Murree Group sequence has conformable contact with underlying Subathu formation. The Murree Group is classified into Lower and Upper Murree formations and their equivalent rocks are designated as Dharmashala Group, Dagshai/Kasauli Formations in Himachal Pradesh. Singh and Andotra (2000) concluded barrier, lagoonal and tidal environment for the Murree sequence. Whereas Rangarao (1971) and Mehta and Jolly (1989) suggested initiation of the fresh water conditions in the Murrees.

2.3. The Bengal Basin

The break-up of eastern Gondwanaland and collision of the Indian plate with the Asian plate are all directly related with the Geologic evolution of the Bengal Basin starting from Upper Palaeozoic. The sedimentary cover of the basin with a maximum thickness of 20 km includes three major lithostratigraphic units separated by three major unconformities. The western part of Bangladesh is the platform shelf, whereas the eastern part of the country is represented by the folded belt (Chittagong-Tripura Fold Belt). The most subsided central part of the basin comprises two major depressions at the north (Sylhet Trough) and south (Patuakhali Depression).The influx of huge amounts of detritus originating from the nearby sources of the basin compensated for the rapid subsidence of the fore-deep of the Bengal Basin. Shallow water conditions and deltaic environment persisted. In addition to the western and northern foreland shelves, which were the earlier source areas, increases erosional rates of the rising chains of the Himalaya and the Indo-Myanmar Ranges provided the much needed sedimention the basinal area since the mid-Miocene (Shamsuddin and Abdullah, 1997).The evolution of Bengal basin as suggested by Alam *et al* (2003) occurred in the following sequence:

I) Permo-Carboniferous to Early Cretaceous syn- rift stage

II) Cretaceous to Mid Eocene drifting stage

III) Mid Eocene to Early Miocene early collisional stage

IV) Early Miocene to Mid Pliocene and

V) Mid Pliocene to Quaternary as late collisional stages.

The sediment depocentre of Bengal basin changes throughout the geological time (Uddin and Lundberg, 2004). These studies infer that during Cretaceous the depocentre was on stable shelf and shifted eastward to Assam during Eocene. Further during Miocene it moved to north-eastern part in the Sylhet trough and during Pleistocene and Pliocene depocentre moved throughout the basin. Presently the depocentre is located at the Hatia trough and Bengal deep sea fan (Alam 2003; Uddin and Lundberg 2004). This depocentre migration appears to have controlled the sedimentation and Stratigraphy in the Bengal basin.

Plate collision and orogeny along its eastern and northern margins resulted in the gradual closure of the Bengal basin which was formed by rifting from passive continental margin (Rowley, 1996). The basin, which attains a maximum thickness of 20 km in its deeper parts, has been filled by an extremely thick accumulation of sediments, mostly of clastic origin. The Bengal basin has two broad tectonic provinces: (1) the Indian platform, where thin sedimentary strata overlie rocks of the Indian craton in the northwest (in northwestern part of Bangladesh); and (2) a very thick basin-fill that overlies deeply subsided basement of undetermined origin in the south and east (Bakhtine, 1966; Khandoker, 1989). The two provinces being separated by a northeast-trending hinge zone (Fig. 2.1). Indian continental crust extends beyond the hinge zone toward the southeast (Khandoker, 1989).

The outermost part of the zone of compression between the west Burma block and the Indian plate is marked by the eastern fold belt. The complexity and amplitude of the north-south-trending folds in this belt decreases and broadens westward. Folding intensity rapidly attenuates westwards; the central and western parts of the basin are relatively under-formed. Pliocene to recent being the main age range of the folding and more than one phase of deformation is evident in some structures. The Sylhet trough is a sub-basin of the Bengal basin in north-eastern Bangladesh which is characterized by large, closed, negative gravity anomaly. The Sylhet trough has minimal topography and is actively subsiding (Holtrop and Keizer, 1970) with an estimate sediment thickness range from about 12 to 16 km (Hiller and Elahi, 1984). The eastern part of the Sylhet trough lies in the frontal zone of the Indo-Burman Ranges.

Accretionary prism development is believed to be the main driving force for the structural evolution of Chittagong-Tripura Fold Belt Basin and major east-dipping thrust faults produced by off-scraping of the oceanic sediments as a result of oblique subduction of the Indian plate beneath the Burma plate in an arc-trench setting (Gani and Alam, 1999). Within the individual major thrust sheets, the sediments in the upper part have been deformed by the activity of thin-skinned tectonics giving rise to a series of elongate, north–south trending curvilinear anticlines and synclines in this province; Sikder and Alam, (2003);Lohmann (1995) and Sikder (1998) have pointed out some duplex structures in the western part of Chittagong-Tripura Fold Belt.

2.4. SHILLONG PLATEAU

This plateau was uplifted to its present height (average 1 km, maximum 2 km) during the Pliocene Epoch. The Shillong plateau is bounded by the Garo-Rajmahal trough fault to the west and the Dauki fault in the south(Johnson and Alam, 1991). “Late Mesozoic and Cenozoic sedimentary rocks drape portions of the southern Shillong plateau and generally dip south in a monocline. The contact between the Shillong plateau and the Sylhet trough is indicated by the poorly exposed Dauki fault. The 5 km wideDauki fault has a nearly straight face across the essentially flat topography which is characterized by extensive fracturing (Evans, 1964) and near vertical (858) dips of Pliocene and Pleistocene strata (Khan, 1978). The Precambrian rocks of the Shillong plateau belong to two groups: (1) an Archean gneissic complex; and (2) the Proterozoic Shillong Group. The gneissic complex, exposed in the northern and western part of the plateau, consists of quartzo-feldspathic gneiss and schists (Rahman, 1999). The boundary between the Gneissic complex and Shillong Group is marked by a lithological as well as structural break. The Proterozoic rocks have undergone regional metamorphism up to garnet-grade prior to the igneous activity in the area. The Shillong Group was overlain by Mesozoic to Miocene rocks prior to the Pliocene uplift of the Shillong plateau (Johnson and Alam, 1991).

2.5. INDO-BURMAN RANGES (IBR)

The Indo-Burmese Ranges occurring along the eastern margin of the Indian sub-continent are a clear representation of oblique collision of the Indian and Eurasian plates. Early Tertiary syn-orogenic sequences, which have been deformed into imbricate thrust zones are the principal constituent of the Indo-Burmese Range and are prominent geo-tectonic elements of South Asia. The Indo-Burmese Ranges has a general north-south trend and is an active orogenic belt, comprising of folded, thrusted and wrench-faulted outer arc complex, or accretionary prism, that accreted to the edge of the Eurasian Plate beginning the Jurassic (Graham *et al*., 1975; Rangarao, 1983).With an average width of 230 km., the ranges extend from the southern tip of the Mishmi Hills into southwest China. Mitchell, (1993) divided the ranges into two orogenic belts: the western belt, comprising the Cretaceous to Eocene sedimentary rocks; and the eastern belt, consisting of schist’s and turbidites. The eastern belt is locally overthrust by serpentinized harzburgites with pillow lavas and hornblende gabbros. The Eocene rocks along the west coast of Arakan in the eastern belt of Indo-Burmese Ranges are being unconformably overlain by the Miocene sediments. Several authors (Mitchell, 1993; Das Gupta and Nandy, 1995) have suggested the possibility of the Indo-Burmese Ranges being trench deposits containing ophiolitic mélanges that got scrapped off the Indian plate.

2.6. SURMA BASIN

The name ‘Surma Series’ was first introduced by Evans (1932) after the Surma River in the Sylhet district of Bangladesh (Dasgupta, 1982). The Surma basin is characterized by a series of continuous and discontinuous north-south trending (N15°E to S 15°W) sub parallel enechelon regional anticlinal ridges and synclinal valleys. The oblique subduction of the Indian plate under the Burma plate has produced a westward migrating accretionary prism complex (Dasgupta and Nandy, 1995; Gani and Alam, 1999). This accretionary prism represents remnant ocean basin sediments (Graham et al., 1975 and Ingersoll et al., 1995). The Surma basin sediments are characteristic of mega rhythmites and bedding cycles indicative of systematic fluctuation in the basinal and source area (Sarkar and Nandy 1977).

The Neogene Surma basin is bounded by the post-Barail unconformity, subsequently faulted (Kaladan fault) to the east; the E-W Dauki fault and NE-SW Disang thrust to the north and northeast; the NE-SW Sylhet fault (Nandy *et al.*, 1983), also term as the ‘Hail – Hakula’ (Ganguly, 1993) lineament and Barisal-Chandpur high concealed below the alluvium of Bangladesh (Sengupta, 1966) to the west and north west. To the south, the basin extends upto the Arakan coastal area of Myanmar. Within this vast terrain, the Surma group and the younger sediments occur as westerly convex N-S fold belt for a strike length of about 550 km, having a maximum width of 200 km. The Surma basin covers lower Assam, Tripura, Mizoram, western part of Manipur, Sylhet and Chittagong districts of Bangladesh and Arakan coastal zone of Myanmar. To the east of this basin lies the intricately folded, faulted and thrusted Palaeogene outer arc complex of the Indo-Myanmar mobile belt, where as to the west, alluvium covered, gently dipping, homoclinal Tertiary sedimentary succession of Bangladesh (Bengal Basin) occurs. This assumes a ‘bell shaped’ form having constant southerly and south-westerly palaeo-slope which connected to the open sea in the south.

The Surma basin is a Neogene outer arc basin, which exposes the alternate arenaceous and argillaceous sequences as rhythmites, reflecting epeirogenic movements throughout the time of deposition (Sarkar and Nandy 1977). The name 'Surma Series' was first introduced by Evan (1932) after the Surma River in the Sylhet district of Bangladesh (Dasgupta 1982). The Surma basin is characterized by a series of continuous and discontinuous north-south trending (N15°E to S 15°W) sub parallel enechelon regional anticlinal ridges and synclinal valleys. The oblique subduction of the Indian plate under the Burma plate has produced a westward migrating accretionary prism complex (Dasgupta and Nandy, 1995; Gani and Alam, 1999). This accretionary prism represents remnant ocean basin sediments (Graham et al., 1975 and Ingersoll et al., 1995). The Surma basin sediments are characteristic of mega rhythmites and bedding cycles indicative of systematic fluctuation in the basinal and source area (Sarkar and Nandy 1977).

2.7. GENERAL GEOLOGY OF MIZORAM

Mizoram is considered to be a major part of Neogene Surma basin which constitutes the southern extends of the basin. Geologically it is an accretionary belt of the Tripura-Mizoram basin represented by successive repetition of Paleogene and Neogene sediments (Evans 1964). This area is related to the eastward subduction of the Indian plate during Eocene following the formation of the Indo-Burman Orogenic belt (Nandy, 1982). Compressive forces brought about by subduction of Indian plate led to crustal shortening and increase in vertical thickness. Continued convergence resulted in N-S trending and E-W dipping anticlines and synclines plunging longitudinally (Ganju, 1975; Ganguly, 1975, 1983).

The first works regarding the stratigraphic set up of the Surma basin was erected by Evans (1932).The main rock facies exposed in the Mizoram area of the Surma Basin are sandstone, siltstone, shale mudstone and their admixtures in various proportions and few pockets of shell limestone, calcareous sandstone and intra-formational conglomerate (Tiwari and Kachhara, 2003).The sedimentary sequence of Mizoram is divided into 3 distinct groups which are Barail, Surma and Tipam by Karunakaran (1974) and Ganju (1975). Tiwari and Kachhara (2003);Mandaokar, (2000) and Tiwari et al., 2011, made some modifications aided by advancement in technology and rigorous geological investigations leading to the present stratigraphic framework of Mizoram which are sequentially grouped into the Barail (Oligocene), the Surma (Lower to middle Miocene) and the Tipam groups (upper Miocene to early Pliocene)

Table 2.1: Stratigraphic framework of Mizoram after Karunakaran, (1974) and Ganju, (1975).

Age	Group	Formation	Unit	Thickness (m)	General Lithology	Depositional Environment
Recent	Alluvium	-	-	-	Silt, clay & gravel	River deposits
Early Pliocene to Late Miocene	Tipam	-	-	+900	Friable sandstone with occasional clay bands	Stream deposits
Miocene to Upper Oligocene	SURMA	Bokabil	-	+950	Shales with siltstone and sandstone	Shallow marine
		Bhuban	Upper Bhuban	+1100	Arenaceous with sandstone, shales and siltstone	Shallow marine, near shore to lagoonal
			Middle Bhuban	+3000	Argillaceous with shales, siltstones	Deltaic complex
			Lower Bhuban	+900	Arenaceous with sandstone, shales and siltstone	Shallow marine
Oligocene	Barail	-	-	+3000	Shales, siltstone and sandstones	Shallow marine
Data source	Karunakaran, 1974; Ganju, 1975				Tiwari and Kachhara, 2003; Mandaokar, 2000; Tiwari et al, 2011, 2012	

2.7.1. GEOLOGY OF THE STUDY AREA

The area for the present study comprises Lunglei town and its surrounding area which is located to the South of Aizawl city between 92°42’45” E - 92°50’05” E longitudes and 22°48’18” N - 22°56’55” N latitudes. The area consists of a series of NW-SE trending anticlines and synclines plunging in N-S directions. The anticlines are overturned consisting of high to moderately dipping Eastern limb while the western part is characterized by sharp ridgelines and vertical cliff face as a result of intense weathering and erosion of highly sheared rocks.

The main litho-unit of the study area comprises of a repetitious sequence of argillaceous and arenaceous sedimentary rock of the Surma Group of rocks. The sedimentary formations vary from fine grey sandstone to fine to medium brown colored sandstone alternation with shales of varying proportions of clay and silt size particles. Based on the stratigraphic framework of Mizoram the rock exposure in the study area is divided into two groups namely the Upper Bhuban and Middle Bhuban formation of Middle to upper Miocene.

The Middle Bhuban formation dominates the Southern part of the Town and adjoining areas. It is dominantly argillaceous with thick shale beds and occasional sandstone beds. The shales are splintery mostly grey, olive green to yellowish brown in color and exhibits weathering patterns like spheroidal patterns some showing fissility based on their mineralogical composition. Silty shale and silty sandstone beds are frequently encountered throughout the area. Sandstone beds are scanty within this area sometimes alternating in thin successions with shale beds. The Northern part of the study area and upper part of the main anticline are mostly dominated by thick and dominant sandstone sequence of the Upper Bhuban formation. These rocks conformably overlie the Middle Bhuban formation. The sandstones are mostly brown, grey to dark grey in color with different ranges of thickness form massive beds to thin beds alternation with shale formations.

Rocks exposed along the roadside section from Tlawng Bridge to Pukpui are mostly dominated by sandstone formations of the Upper Bhuban rocks. This roadside section runs parallel to the fold axial line which plunges gently towards the North. The sandstones are brown to grey in color showing varying thickness of stratification which can be interpreted as frequent fluctuations in environment with mixed source of sediment supply and shallow depositional environment. Shales beds of differing proportions alternate with the sandstone formations especially in the lower part of the section. The shales are bioturbated with trace fossil signatures that depict high rate of deposition. Upper part of Pukpui, Zotlang, Serkawn and Zohnuai localities are situated along the crest of the main Lunglei anticline. The upper part of this section exposes buff sandstone formations which represents the youngest part of the anticlinal limb. These are fragile sandstones with weak physical properties due to larger grains size, high porosity and weak cementation and hence the colluvium cover in this area is thicker due to high weathering rate due to oxidation of ferruginous sandstones. These geological factors greatly contribute to the difference in topography and thick vegetation cover in this section especially in Kawmzawl and adjacent areas.

The main part of the town is governed by sandstone dominated lithological successions which is quite similar to the rock formations exposed in the Northern part of the study area. The main road follows the ridge line with steep cut slope on the western side and moderately dipping eastern bed where most of the population is concentrated. Beyond Lunglawn and adjacent areas including Hauruang and Vanhne the lithological transitioned into a more argillaceous dominant type with grey and olive green splintery shales exposed along the road side sections. This stratigraphic succession in this area is considered to be rocks of the Middle Bhuban formation of Surma group of rocks. Sandstone bed are found occasionally alternating with shale beds and sometimes exposed as massive bedded formations which could be an indication of uplift event or storm conditions. Several trace fossils are found within the area which depicts the changes in paleo environment of the area during the period of deposition. The Southernmost part of the section form Hrangchalkawn - Thaizawl road to the South and Zobawk road to the East exposes dominant grey sandstone formations with occasional shale alternations. The rocks are very fine to fine grained with several sedimentary structures like laminations, heterolithic bedding etc. Regardless of the structures the rock are mined by quarrying and are the main source of building rocks due to high demand in the area.

Fig. 2.1 : Grey Sandstone with shale on top

Fig. 2.2: Thickly bedded sandstone with prominent joint set

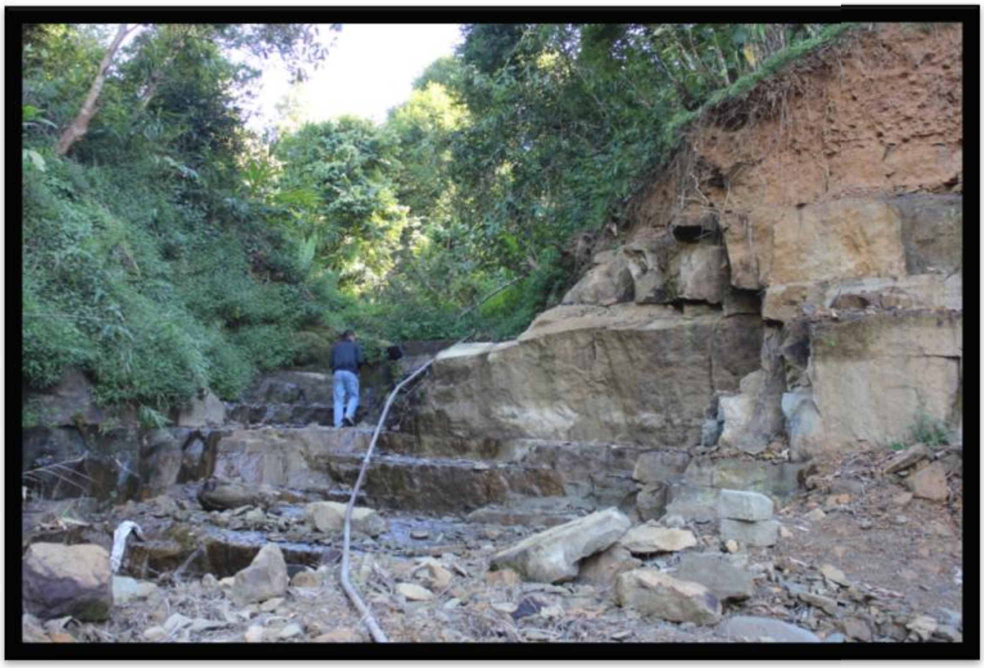


Fig. 2.3: Thickly bedded brown sandstone

Fig. 2.4: Grey sandstone with brown sandstone on top

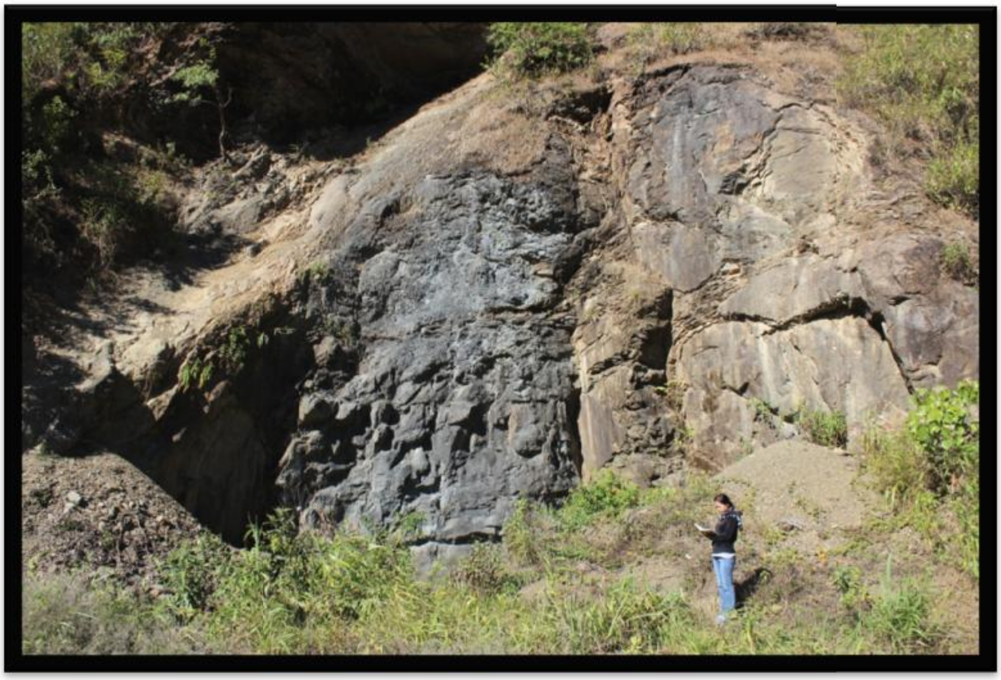


Fig. 2.5: Siltstone-shale alternation with exfoliation

Fig. 2.6: Grey sandstone with siltstone on top

Fig. 2.7: Silty sandstone with thick colluvium

Fig. 2.8: Thick colluvium deposits

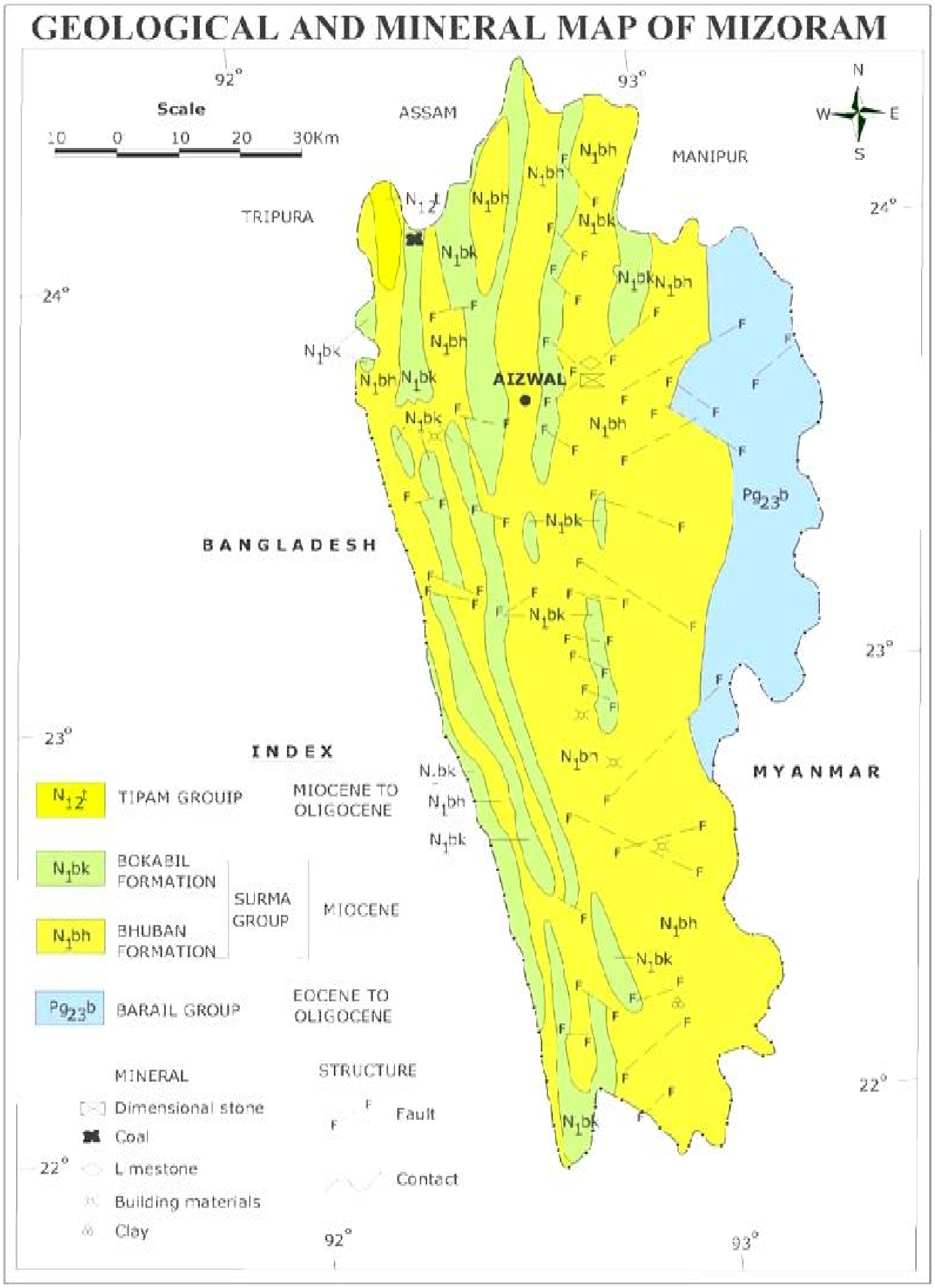


Fig.2.9: Geological map of Mizoram according to Geological Survey of India.

3. METHODOLOGY

3.1. Introduction

The present study is an attempt to assess the landslide susceptibility of Lunglei town and its vicinity by GIS technique using Frequency Ratio method. The frequency ratio method is a simple and reliable method which is widely applied for the mapping of landslide susceptibility. The methodology of the study is based on the principle adopted by Varnes (1984) which states that "the slope failures in future will most likely be in geologic, geomorphic and hydrologic situations that have lead to past and present failures." The first important data needed for the study is the landslides location points for the preparation of Landslide Inventory map, this means that landslide inventory map forms the basis of the study. Secondly, thematic layers for the causative factors of the landslides are required. There are numerous terrain conditions which are classified as geological, topographical and environmental conditions which have been used. The identification of the factors responsible for the landslides in an area will depend on the knowledge and type of landslides (Guzzetti *et al*., 1999).

The preparation of Landslide Susceptibility Zonation Map (LSZM) of Lunglei town and its vicinity was carried out in six steps. i) data collection ii) database generation iii) preliminary analysis, iv) validation v) evaluation of the relationship between the landslides and input data and vi) final preparation of LSM.

The basic data sources are the Survey of India Toposheets (1:50,000 scale with 10m contour interval), digital elevation model obtained from Alospalsar (www.landsat.org) as free download, landslide inventory map was prepared by extensive fieldwork, rainfall data obtained from Directorate of Agriculture and Directorate of Economics and Statistics and other data needed for the preparation of thematic layers were also obtained from Mizoram Remote Sensing Applications (MIRSAC)

3.2. Geographic Information System

According to Rhind (1989) Geographic Information system (GIS) is a system of hardware, software and procedures designed to support the capture, management, manipulation analysis, modelling and display of spatially referenced data for solving complex planning and management problem. “However, it is a computer system capable of assembling, storing, manipulating, and displaying geographically referenced information, i.e., data identified according to their locations” (USGS 1997). A fundamental characteristic of a Geographic Information system (GIS) is its ability to handle spatial data, i.e., the locations of objects in a geographic space, and the associated attributes. Normally, the geographic space is on the surface of Earth on which we live. A map is the most efficient shorthand to show locations of objects with attributes and their spatial distributions. These objects can be physical or cultural in nature. The unique feature of GIS is the ability to analyse the database and to arrive at solutions for management. The following 4 sets of capabilities to handle georeferenced data can be provided by Geographic Information System (GIS):

1. Data capture and preparation,
2. Data management (storage and maintenance),
3. Data manipulation and analysis and
4. Data presentation.

3.2.1. Vector data

Points are pairs of x, y coordinates, lines are sets of coordinate pairs that define a shape, and polygons are sets of coordinate pairs defining boundaries that enclose areas. Coordinates are of often pairs (x, y) or triplets (x, y, z, where z represents a value such as elevation). The coordinate values depend on the geographic coordinate system in which the data is stored. ArcGIS stores vector data in feature classes and collections of topologically related feature classes. The attributes associated with the features are stored in data tables.

In ArcGIS, three different implementations of the vector model are used to represent feature data viz, coverage's, shapefiles, and geodatabases. Vector data models are useful for representing and storing discrete feature such as buildings, pipes or parcel boundaries.

3.2.2. Raster data

A raster model known as image data sets, in its simplest form is a matrix (grid) of cells. Each cell has width height and is a portion of the entire area is represented by the raster. The dimension of the cells can be as large or as small as needed to represent the area and the features within the area, such as square kilometres, square meter, or even square centimetre. The cell size determines how coarse or fine the patterns or features will appear. The smaller the cell size, the more detail the area will have. However, the greater the number of cells, the longer it will take to process and it will require more storage space. If a cell size is too large, information may be lost or subtle patterns may be obscured.

3.3. Methods for Landslide Susceptibility Mapping (LSM)

The methodology for the preparation of landslides susceptibility map involves the following steps:

- Preparation of digital database of spatial data which are related to landslides
- Classification and reclassification of the data
- Intersect analysis to calculate the frequency ratio
- Assigning the calculated frequency ratio to the thematic layers
- Weighted sum analysis and calculation of landslide susceptibility index
- Suitable classification of landslide susceptibility and validation.

3.4. Collection and preparation of Different Data sets

Toposheets used for the study were 84 B/9 and 84 B/13 with scale of 1:50,000 which was prepared by the Survey of India. The toposheets were scanned in JPG format and in order to use in GIS environment, it was again georeferenced using Ground Control Points (GCP) and the features were digitized in ArcGIS software. Certain features such as roads, drainage, rivers, settlements and contours were extracted from the toposheets. Moreover, thematic layers like drainage density and distance to drainage were prepared from the drainage map obtained from the toposheets.

Quick bird and world view satellite imagery having spatial resolution of 0.8 m obtained from Mizoram Remote Sensing Application Centre (MIRSAC) and Resourcesat-2: LISS-III was used for the preparation of thematic layers needed for the study.

SPECIFICATIONS	LISS-III
No. of Bands	4
Spectral Bands (µ)	B2 0.52 – 0.59 B3 0.62 – 0.68 B4 0.77 – 0.86 B5 1.55 – 1.70
Resolution (m)	23.5
Swath (Km)	140

Table 3.1 : Specifications of Resourcesat-2: LISS-III

Landslides data were collected using Glonass Handheld GPS within the study area. On the otherhand, rainfall records were collected from Directorate of Agriculture and Directorate of Economics and Statistics, Govt.of Mizoram. The rainfall data record was collected from the year 1999 to 2019. These rainfall data were used to understand the relationship between the rainfall and landslide events.

Previous literature is an important tool for landslide studies so a maximum number of literatures related to the studies were collected from different national and international journals and books.

Software used for the study:

- ArcGIS 9.3 and ArcGis 10.3
- SAGA 6.3.0 (System for Automated Geoscientific Analysis)
- QGIS 3.12

3.4.1 Preparation of Different Data set: The thematic maps for the causative factors was prepared by extracting the information from Survey of India Toposheet and Satellite imagery.

- From Toposheets : Elevation and Drainage
- From satellite imagery:
  - Landuse/Landcover
  - Structure
  - Lithology
- By Fieldwork : Landslides location using GPS
- By GIS analysis :
  - DEM
  - Slope
  - Drainage density
  - Distance to drainage
  - Plan curvature

3.5. Landslide Inventory Map

Landslides are a complex natural phenomenon that constitutes a serious natural hazard in many countries (Brabb and Harrod, 1989). Landslide inventories contain basic information about landslides such as location, classification, morphology, volume, run-out distance, activity and date of occurrence/activity (Wieczorek, 1984; Fell *et al*., 2008). Inventories are prepared using different techniques depending on the scope of the work, the extent of the study area, the scales of base maps, the quality and detail of the accessible information, and the resources available to carry out the work (Guzzetti *et al*., 2000). Accurate landslide inventory map is the basic requirement for quantitative assessment of landslides (Chacón *et al*., 2006).

Since there is no detailed historical landslide records of the present study area, the location of landslides that have taken place in 2013-14 were used. As mentioned before the landslide data were collected by extensive fieldwork to prepare the landslide inventory map. With changing climate and weather the morphological features of the landslides are changing within a period of time and identification of such landslides becomes difficult in certain location. This could be due to different reasons such as natural ones like growth of vegetation or successive land sliding, removal of toe for remedial works and anthropogenic modification of slope for subsequent agricultural activity.

In order to prepare Landslide Inventory Map, extensive fieldwork was carried out within the study area. Landslide location points were collected using handheld GPS and a total number of 152 landslides were recorded during the year 2013 and 2014. During these fieldworks, necessary information related to the studies such as the rock type, types of slides, landuse etc were also collected and recorded for the research. The landslide points were plotted as point features on the georeferenced toposheets in ArcGIS.

3.6. Preparation of the Thematic map for different causative factors of Landslide.

In this study 7 causative factors namely slope, landuse, drainage density, distance to drainage, structure, plan curvature and lithology were used for preparing the Landslide susceptibility map. The thematic map for each factors were prepared, the layers for slope, drainage density and distance to drainage, structure and lithology were prepared by using ArcGis, and landuse map was prepared using Quantum GIS and ArcGIS while plan curvature was prepared by using SAGA software. SAGA 2.0.7 (System for Automated Geoscientific Analysis) is a free software that can be downloaded from www.saga-gis.org and has many hydrological and terrain analysis capabilities. QGIS 1.7.0 (Quantum GIS) is also licensed under the GNU General Public License and supports many common spatial data formats (eg. ESRI shapefiles, geotiff). The advantage of QGIS is that you can add Google Earth using the open layer plugin. In addition to standard terrain analysis it can generate ruggedness index. Several layers given below were created by Terrain Analysis modules of the GIS softwares and were evaluated for their relationship with landslides. A description of each data layer preparation and the general characteristics are given in the following pages.

DEM derivatives (Generated from elevation data obtained by digitising the contours from Toposheet)

1. Slope
2. Plan Curvature

Drainage derivatives

1. Drainage Density
2. Distance to Drainage

Satellite Data & Google Earth

1. Landuse Map
2. Structure Map
3. Lithology Map

3.6.1. Digital Elevation Model (DEM):

DEM is the spatial extent of the elevation of the region and has been used to derive slope and plan curvature. The DEM is prepared by digitising the contours at 10 m interval from Survey of India Toposheets. The line data is converted into point data and the DEM was created with Spatial Analyst in ArcGIS by interpolation using Topo to raster tool. The spatial resolution of the DEM used for creating the thematic layers is 30m. The DEM is not only used to create the various thematic layers used in the analysis but also was used to create the hillshade of the study area.

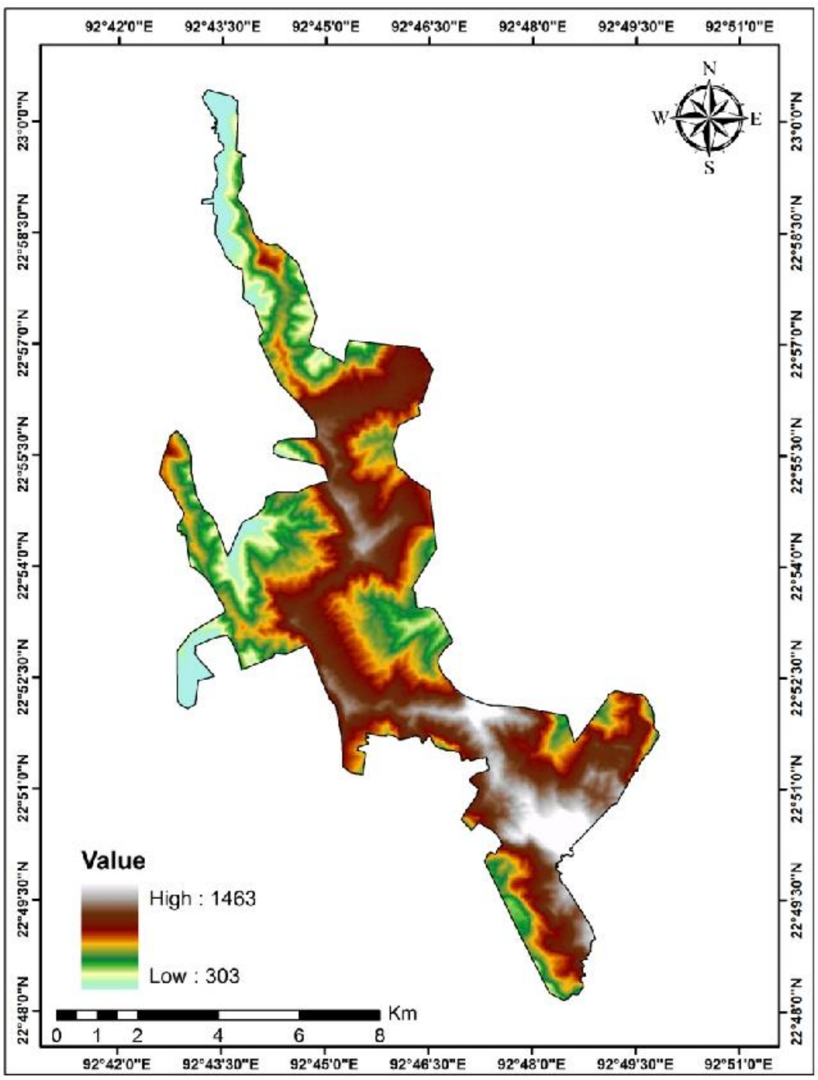


Fig. 3.1 : Digital Elevation Model (DEM) of the study area

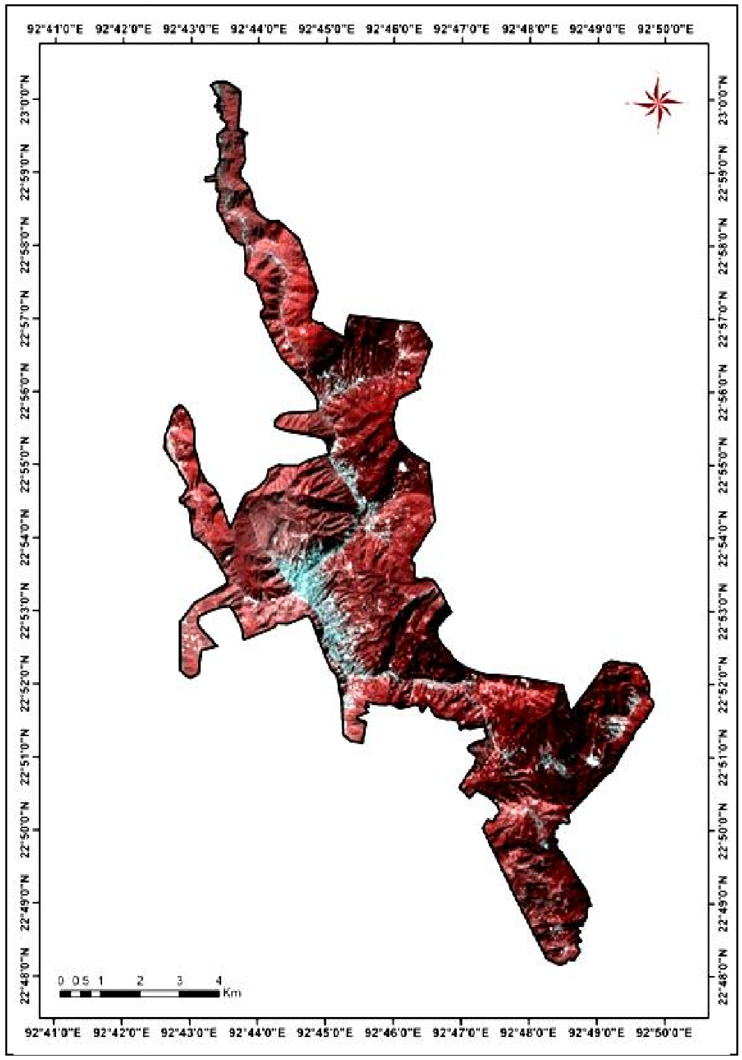


Fig. 3.2: LISS III Satellite Imagery: False Colour Composite (FCC) of the study area

Fig. 3.3 : Collecting Landslide location points

Fig. 3.4 : Collecting Landslide location points

Fig. 3.5 : September 14, 2014 Landslides at Lunglawn locality, Lunglei

Fig. 3.6 : Landslides on 17 September 2014 at Lunglawn

Fig. 3.7 : House destroyed by Landslide on 18 August 2019.

Fig. 3.8 : Houses dismantled by landslide at College veng locality, Lunglei

3.6.2 Slope

Slope is a very important parameter in any landslide hazard zonation mapping. If the slope is high then there is a chance of occurrence of landslide. Interpolation of DEM was made to generate a slope map using spatial analyst extension available in ArcGIS. Since the data is in tiff format, it was again exported as imagine format which was used for the generation of slope map. The pixel size of the slope map is kept as 30 x 30 m. In the study area slope varies from 5° to 73°. The slope map generated is in Raster format and classified into five classes viz., 0 to 5°, 5 to 15°, 15 to 25°, 25 to 35° and >35°.

3.6.3 Drainage map

A drainage map has been generated by digitizing the drainage lines from Survey of India toposheets. The first order streams were digitized first followed by II, III, IV,V and VI order streams and the order is given in the attribute table that the stream ordering can be depicted in the drainage map prepared. The drainage map has subsequently been used for generating drainage density maps, stream order maps and distance to drainage map using the tools in GIS. The drainage density map and distance to drainage maps have been used as an input for the generation of landslide susceptibility map.

3.6.4 Drainage density map

Drainage density is defined as the cumulative length of drainage per unit area. It provides a measure of ground water infiltration viz. surface runoff occurring in an area. Low drainage density implies low surface runoff and higher infiltration to groundwater, which may increase the slope instability in a region (Sarkar and Kanungo 2004). In this study, the drainage streams have been digitized from topographic maps and the drainage density map was prepared using line density tool in Spatial Analyst, in the ArcGIS. Drainage density map was prepared using the Density tool in extension Spatial Analyst of ArcGIS. The drainage density was classified into five classes which ranges from 0 to 7.84 km/km^2.

3.6.5. Distance to Drainage

The distance to drainage is also an important landslide controlling factor. The distance to drainage map was prepared by creating multiple ring buffer with 50m and 100m as the distance for each buffer using analysis tool in ArcGIS. Since this layer is in vector format the layer is then converted into Raster format using Spatial Analyst extension for overlay analysis. Distance to drainage map was classified into 5 classes viz.0-50m, 50-150m, 150-250m, 250-300m and >350m

3.6.6. Landuse/Land cover map

A landuse/landcover map shows distribution of forest cover, water bodies, and types of land use practices. The land-use pattern or vegetation cover plays the important role on the stability of slopes. Several researchers (Koukis and Ziourkas, 1991; Anbalagan, 1992; Maharaj, 1993; Gokceoglu and Aksoy, 1996; Fernandez *et al.*, 1999; Guzzetti *et al.*, 1999; Luzi and Pergalani, 1999; Zezere *et al.*, 1999; Uromeihy and Mahdavifar, 2000) emphasized the importance of vegetation cover or land-use characteristics on the stability of slopes and they used these to assess the conditioning factors of the landslides. The occurrence of landslides varies with land use/cover pattern, which is an indication of the stability of hill slopes (Anbalagan 1992). Land use/land cover map is produced by digitizing the worldview satellite imagery of the study area. After careful analysis of the satellite imagery, fieldwork was carried out to have a ground truth survey in order to prepare a reliable landuse/landcover map. The landuse/landcover identified in the study area were agriculture plantation, jhum/cultivated land, built up/settlements, scrubland, less dense forest, open forest and waterbody.

3.6.7. Lithology

Lithology is one of the major parameters for landslide hazard zonation (Sharma et al., 2011). The geology of Mizoram consists of great flysch facies of rocks comprising monotonous sequences of shale and sandstone (La Touche, 1891). The study area is underlain by Middle Bhuban and Upper Bhuban formation of Middle to upper Miocene. "In the study area a repetitious sequence of argillaceous and arenaceous sedimentary rock of the Surma Group of rocks are present and the sedimentary that are exposed are fine grey sandstone to fine to medium brown sandstone colored. These sandstones are present alternation with shales. Silty shale and silty sandstone beds are frequently encountered throughout the area. Upper Bhuban formation comprises mainly of arenaceous rocks with sandstone as the dominant rock type with subordinate amount of shale, siltstone with occasional clay bands".(Lallianthanga R.K.*et al*., 2013). The lithology map prepared by the Geological survey of India was used as the base map in order to prepare the lithology map of the study area. Shapefile for lithology was created as polygon feature type and all the lithological unit present within the study was digitized. Six litho-units-sandstone, shale-sandstone, siltstone-shale, shale-siltstone, crumpled shale and gravel,sand,silt & clay unit are present in the area. "Soft rock units comprising of shale erode faster and are easily weathered" (Anbalagan *et al*., 2008), and are therefore considered more susceptible to landslide than the hard and compact sandstone units.

3.6.8. Plan Curvature

Planform curvature (commonly called plan curvature) is perpendicular to the direction of the maximum slope. In order to prepare thematic layers for plan curvature, the digital elevation model (DEM) was used as the main data. Positive value indicates the surface is sidewardly convex at that cell. A negative plan indicates the surface is sidewardly concave at that cell. A value of zero indicates the surface is linear . ArcGis and Saga software were both used for generating the Plan curvature of the study area

3.6.9 Structure

Remote sensing data can be utilised to delineate and analyse the geological structures like faults, fractures, joints, etc. (Sakar & Kanungo, 1995). These geological structures are among the most important parameters for Landslide Hazard Zonation (Saha *et al.,* 2002). It was observed that the rocks exposed within the study area were traversed by several faults and fractures of varying magnitude and length

(MIRSAC, 2006). Areas located within the vicinity of faults zones and other geological structures are considered more vulnerable to landslides. For the preparation of structure map the radius used for the generation of the structure density map was 1 km and the cell size was selected as 30 m. The structure layer was classified into five classes such as very low, low, moderate, high and very high.

"Structurally, the study area is represented by a NW-SE trending of the eastern limb of Lunglei anticline. The beds generally trend N-S to roughly NNW-SSE and dip on either side from 20^o to 65^o with local variations". (Lallianthanga R.K.et al., 2013). Faults of small magnitude were identified and the lineaments present within the study area are oriented in various directions.

3.7. SAGA :

Plan curvature was prepared by using Saga software. This is done by adding the DEM layers, double click on the DEM layers added and the windows is shown. We can look the description of the layers from the right hand side of the SAGA window. Modules was selected and Terrain analysis was again selected which gives the Standard Terrain analysis, from this the layers can be created. The layers were export to ESRI and the layers for plan curvature were created by giving the grid as 30x30m. However, these layers were in .asc format, they need to be converted into image file.

3.8. Base map

In the preparation of base map the following data are included; settlements, roads and few locality. Toposheet (1:50,000) is the basis for the base map and is prepared by georeferencing a scanned image of the toposheet and digitising the terrain features and settlements, communication network, etc.

3.9. Contours

Contours are generated from the digital elevation model using the spatial analyst tool in ArcGIS and were digitised at 10 meter interval.

3.10. Classification

The thematic layers of the different causative factors is classified based on Natural Breaks (Jenks) method assigning different classes. For example, Slope layers is classified into 0°-5°, 5°-15°, 15°-25° and so on. This classification is done by using ArcGIS, by selecting the properties of the layers, symbology is selected and from this we can classify easily. The other layers are also classified based using this method.

3.11. Hawths Tool

This is an extension tool for ArcGis. Using this tool, 100% of the landslides is divided into 75% and 25%. This is done by selecting the Hawths Tool and click on sampling tool, random selection is created by adding 75%. By right clicking on the landslide tool which is present on the table of contents a layer is created for 75% landslide. 114 landslides points i.e. 75% of the landslides is selected for overlay analysis. The remaining 38 landslides points ie.25% is used for validation.

3.12. Intersect Analysis

In order to find out the frequency ratio for each pixel of the causative factors, intersection has to be done, for this each causative factors such as slope,drainage density, landuse etc. were used. After classification method the layers are reclassified from the Spatial Analyst extension, this is again converted into vector format if the layers are in raster form. From the Arc toolbox intersect analysis is selected by putting the reclassified layer and 75% of the landslide as input features. The intersect polygon for the layers were finally created.

3.13. Frequency ratio method

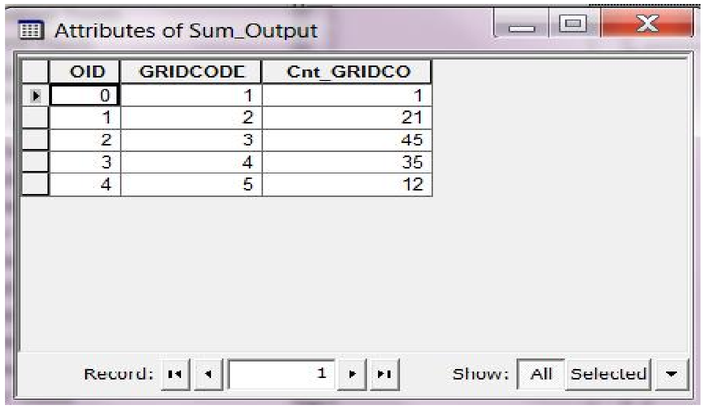
The frequency ratio is the ratio of the area where landslides occurred in the total study area, and also, is the ratio of the probabilities of a landslide occurrence to a non-occurrence for a given attribute. (Lee and Talib 2005). The frequency ratio was calculated by dividing the percentage of landslide in a sub-variable by the percentage of the sub-variable in the total area. For calculating the frequency ratio the raster data set of a thematic layer is vectorised into polygons after reclassifying using Spatial analyst. The landslide inventory map is overlaid on the vector layer and by intersection method using analysis tool, the class in which each landslide falls is obtained. The attribute table of the intersect layer is opened and the class column is summarised. The summary output attribute gives the number of landslides in each sub-variable from which the percentage of landslides is calculated as shown in fig. 3.10. If the thematic layer is in vector format, the layer is directly used for intersection. The area for the subvariables was also calculated. The data from summarised output is used for the calculation of percentage of landslides in each class and the percentages of pixels in domain are also calculated to arrive at the frequency ratio.

Attributes of Slope_Intersect

FID	Shape *	FID_rastof	ID	GRIDCODE	FID_75_Ls	Y	X	RNDSEL
0	Point	8667	866	3	104	22.8277	92.80547	1
1	Point	8302	830	5	103	22.83659	92.80371	1
2	Point	8264	826	4	101	22.83663	92.79908	1
3	Point	8302	830	5	102	22.83693	92.8021	1
4	Point	8175	817	2	105	22.83982	92.79596	1
5	Point	8191	819	3	10	22.84389	92.79636	1
6	Point	7975	797	3	9	22.84608	92.79644	1
7	Point	7817	781	2	13	22.84773	92.81734	1
8	Point	7846	784	2	12	22.84806	92.80173	1
9	Point	7875	787	4	8	22.84853	92.79537	1
10	Point	7968	796	3	15	22.84906	92.80629	1
11	Point	7780	778	4	16	22.84965	92.80602	1
12	Point	7586	758	3	14	22.85279	92.8157	1
13	Point	8128	812	4	11	22.853	92.79958	1
14	Point	7647	764	3	100	22.85333	92.82012	1
15	Point	7532	753	5	7	22.85428	92.79023	1
16	Point	7709	771	5	96	22.85447	92.82412	1
17	Point	7465	746	5	97	22.85606	92.82371	1
18	Point	7157	715	2	94	22.85994	92.75798	1
19	Point	7544	754	3	93	22.86	92.757	1
20	Point	7164	716	4	5	22.86126	92.78671	1
21	Point	7084	708	4	95	22.86137	92.75766	1

Record: 1 Show: All Selected Records (0 out of 114 Selected) Options

Fig 3.9 : An intersection with class sub variables and landslides.



Attributes of Sum_Output

OID	GRIDCODE	Cnt_GRIDCO
0	1	1
1	2	21
2	3	45
3	4	35
4	5	12

Record: 1 Show: All Selected

Fig 3.10 : Output of landslides falling in each sub variable class.

As shown in fig. 3.10. the number of landslide points in each class is listed in the file. From the slope attribute table it can be seen that 1 landslide have fallen in Class 1 in which the slope degree is 0 to 5^0, and in the class where slope angle is 5 to 15, 21 landslides have fallen and so on. Classes without landslides are not displayed in the table and the number of landslides in such class is 0. The percentage of landslides in each class is calculated using the above data in separate excel sheet.

The frequency ratio was calculated for each class of factors as shown below:

$$\text{Frequency ratio} = \frac{\text{Landslide Occurrences\%}}{\text{Pixel domain \%}}$$

Where,

(i) Landslide occurrence =Number of Landslide occurrence present in each class(eg.21)

(ii) Total number of landslides = 114

(iii) Landslide occurrence % = Percentage of Landslides present in a class

(21÷114)×100 = 18.42%

(iv) Pixel domain = Number of Pixel in each class eg. 17233

(v) Number of Pixels in the area = Total number of pixels ie. 74245

(iv) Pixel domain % = Percentage of Pixel domain in a class

(17233÷74245)×100 = 23.21%

$$\text{Therefore, Frequency ratio} = \frac{\text{Landslide occurrence \%}}{\text{Pixel domain \%}}$$

=18.42÷23.21 = 0.79

Frequency ratios having more than 1 means that there is a high probability for the occurrences of landslides and the frequency ratios less than 1 means there is lesser chance for landslides to occur (low probability). Similarly, it can be said that Areas with low Σ Frequency ratio are least susceptible to landslides and those with high frequency ratios have higher landslide susceptibility. The resulting map is classified into five susceptibility zones viz., Very Low, Low, Moderate, High and Very High landslide susceptibility zones.

3.14. Reclassification

For generating the Landslide Susceptibility map and for preparing different thematic layer the classified image is again reclassified by using the Spatial Analyst extension in ArcGIS. The frequency ratio calculated is entered as new values for reclassification and also by selecting change missing values to no data. The reclassified layers in which the calculated frequency ratio was assigned were further used for overlay analysis.

3.15. Overlay Analysis

The integration of different data layers involves a process called overlay. At its simplest, this could be a visual operation, but analytical operations require one or more data layers to be joined physically. This overlay, or spatial join, can integrate data on soils, slope, and vegetation, or land ownership with tax assessment. Overlay analysis can be done by the spatial analyst extension tool in ArcGIS. From this, the weighted sum overlay analysis has been done by adding all the thematic layers created previously. These thematic layers or causative factors are prepared by classifying using natural breaks and again reclassified by assigning the frequency ratio. If these layers are in raster format they are again converted into vector for intersect analysis.

3.16. Landslide susceptibility values

When instability events are numerous and cover large areas, better results are achieved by gathering basic information and examining it through descriptive statistics (Carrara *et al.*, 1982). Some authors (Koukis and Ziourkas, 1991; Ferrer and Ayala-Carcedo, 1997; Zezere *et al.*, 1999) employed simple statistical techniques when investigating the conditioning or triggering factor of the landslides. Therefore in statistical analysis and quantification of landslide hazard is preferred over cartographic approach. To achieve this end the different factors considered were grouped according to their relative importance and landslide frequency ratio were assigned to them by reclassification for the factors viz. Slope, Landuse, Drainage density, Distance to drainage, Plan Curvature, Lithology, Structure

The landslide controlling factors were classified into various categories. For example distance to drainage is divided into six classes viz., 0-50m, 50-150m 150-250m and so on. The frequency ratios of landslides in each class is determined by overlying the landslide inventory map over each factor and are assigned to the classes of the factors. For example the frequency ratio of the classes of distance to drainage are 0-50m=1872, 50-150m=1118,150-250m=792, 250-300m=162, 300-350m=0. These ratios suggest that the distance to drainage 0-50m, 50-150m and 150-250m have highest susceptibility to landslides as their ratios are 1.872, 1.118 and 0.792 respectively.

3.17. Landslides Susceptibility Zones

The landslide Susceptibility Zonation (LHZ) map is classified into five classes very low, low, moderate, high and very high using natural break method of Jenks available in ArcGIS. ArcMap identifies break points by picking the class breaks that best group similar values and maximize the differences between classes. The features are divided into classes whose boundaries are set where there are relatively big jumps in the data values. The landslide susceptibility map (LSM) is prepared with ΣFr. Areas with higher ΣFr is more susceptible to the landslide hazard and areas with low ΣFr are least susceptible to landslide hazard. The LSM have five classes viz., very low, low, moderate, high and very high landslide susceptibility zones (LSZ).

3.18. Effect (influence) Analysis:

Effect analysis studies show how a solution changes when the input factors are changed. If the selected factor results in a relatively large change in the outcome, then the outcomes is said to be effective to that factor. Effect analysis quantifies the uncertainty of each factor. The factors that have the greatest impact on the calculated landslide susceptibility map can therefore be identified using effect analysis. (Lee and Talib 2005)

In this study effect analysis was done by calculating the frequency ratio excluding each causative factors using weighted sum overlay from the spatial analyst tool. From this we can find out which of the causative factors used in the landslide susceptibility have higher influence on the occurrence of landslides in this area.

3.19. Validation:

The landslide inventory map is overlaid on the landslide susceptibility map for validation and the percentage of landslides in each zone is determined to validate the methodology. If the landslides are more in the high hazard zone than the low hazard zone the methodology is validated. Validation of the map is important because unless it is validated the numerical method is useless and cannot be used. The validation is done to whether its predictions matched the expected results. 25% of the landslides not used for overlay analysis were overlaid on the LSM and the number of landslide falling in high and very high LSZ will be determined for validation of the LSM. Higher the number of landslides falling in high and very high hazard zones better is the validation. This means that the landslide inventory map which took into consideration the slope, drainage density, landuse and distance to drainage of the area, is overlaid on the Landslide Hazard Map and the number of landslides falling in each susceptibility zone is calculated.

3.20. Final Landslide Susceptibility Map: After validation the frequency analysis will be attempted based on all the 152 landslide points to produce the final LSM.

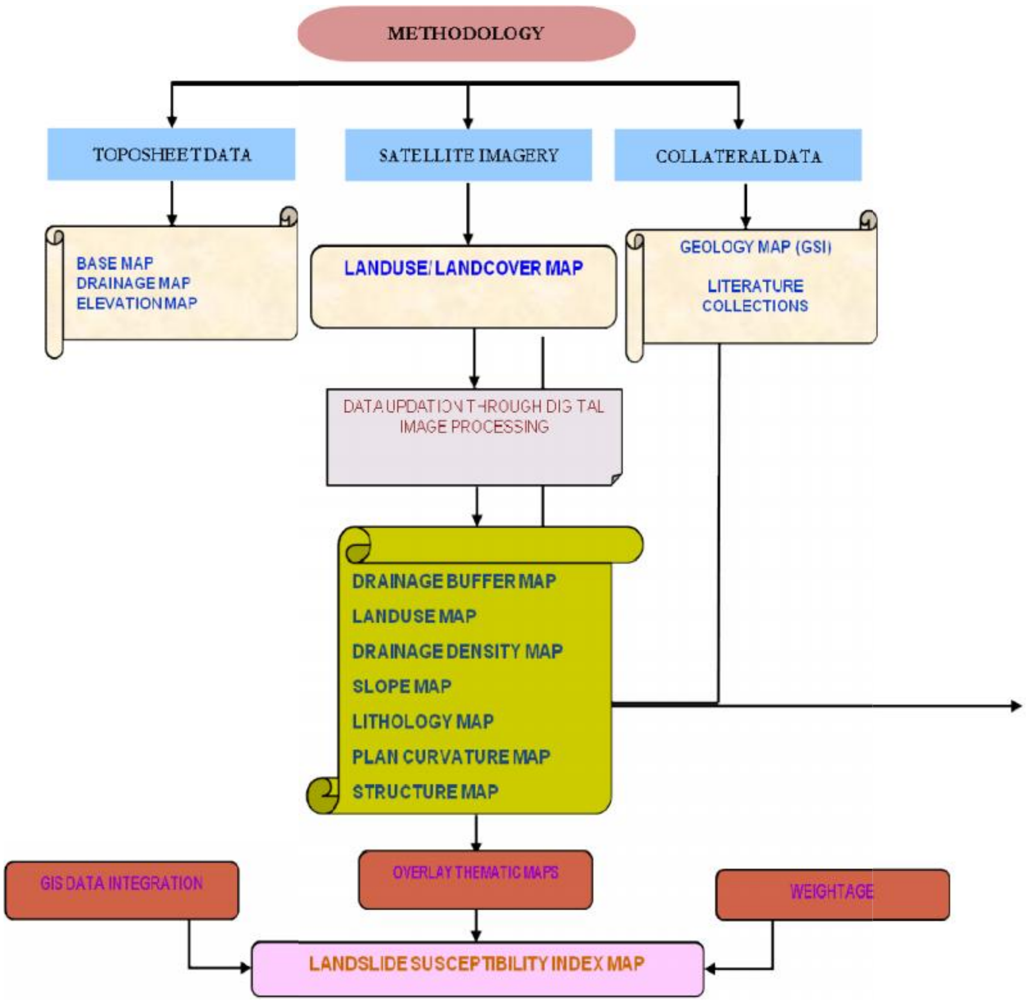


Fig. 3.11 : Methodology Flowchart for the present study.

4. RESULTS AND DISCUSSION

4.1 Introduction:

Landslide Susceptibility Mapping using frequency ratio method had been performed by various researchers and geologist using different parameter depending upon the terrain of the study area and also on the availability of data. “Frequency ratio model was used based on the assumption that future landslides will occur under circumstances similar to those of past landslides” (Lee, *et al*., 2004a). In general, to predict landslides, it is necessary to assume that landslide occurrence is find out by landslide-related factors, and that future landslides will take place under the same conditions as past landslides. Using this assumption, the relationship between landslides occurring in an area and the landslide-related factors can be differentiate from the relationship between landslides not occurring in an area and the landslide-related factors. We used the frequency ratio to represent the distinction quantitatively. The frequency ratio is the ratio of the area where landslide occurred to the total study area as well as the ratio of the probabilities of a landslide occurrence to a non-occurrence for a given factor’s attribute. Therefore, the greater the ratio above unity, the stronger the relationship between landslide occurrence and the given factor’s attribute, and the lower the ratio below unity, the lesser the relationship between landslide occurrence and the given factor’s attribute. To calculate the frequency ratio, a table was created for each landslide-related factor. Then, the ratio of landslide occurrence and non-occurrence was calculated for each range or type of factor, and the area ratio for each range or type of factor to the total area was calculated. Finally, the frequency ratio for each range or type of factor was calculated by dividing the landslide-occurrence ratio by the area ratio.(Lee and Talib 2005; Lee and Pradhan, 2006).

The relationship between the landslide occurrence area and the landslide related factors could be deduce from the relationship between areas where landslides had not taken place and the landslide related factors. To represent this distinction quantitatively, the probability likelihood (frequency ratio) was used. “The probability likelihood (frequency ratio) is the ratio of the probability of an occurrence to the probability of a non-occurrence for given attributes" (Bonham-Carter 1994).

4.2. Field Data

4.2.1. Landslide Inventory Map

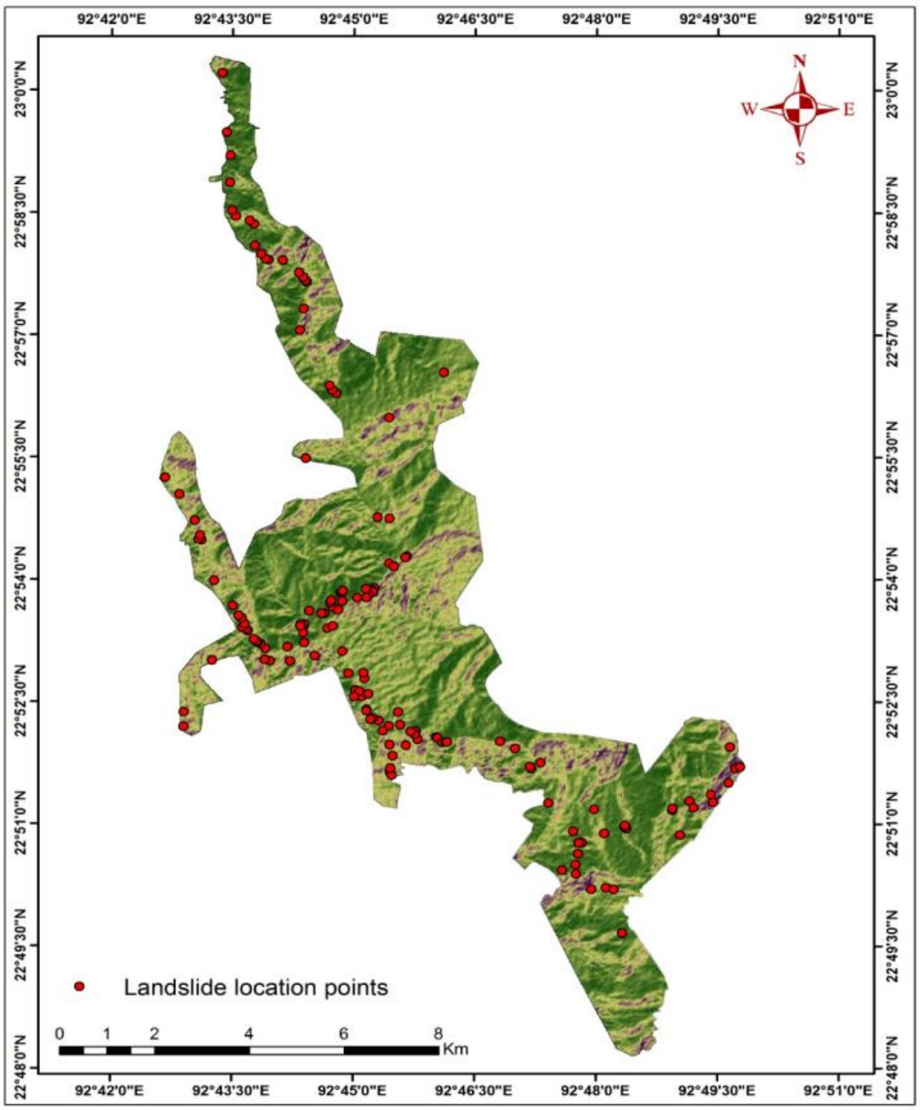


Fig. 4.1. Landslide Inventory Map of the study area.

Landslide inventory map forms the basis of investigation of landslides as the future landslides can occur in the same combination of physical and environmental conditions as in the past landslides (Van Westen *et al*., 2003). Landslide inventories contain basic information about landslides such as location, classification, morphology, volume, run-out distance, activity and date of occurrence/activity (Wieczorek, 1984; Fell *et al*., 2008). Inventories are prepared using different techniques depending on the scope of the work, the extent of the study area, the scales of base maps, the quality and detail of the accessible information, and the resources available to carry out the work (Guzzetti *et al*., 2000). Table 4.1(A to E) shows the number of landslides recorded and the landslide points were plotted as point features on the georeferenced toposheets in ArcGIS.

Table:4.1 (A to E): List of landslides collected with their location coordinates.

Sl.No	Latitude	Longitude
1	22.86772	92.76711
2	22.86763	92.76721
3	22.86754	92.76739
4	22.86666	92.76838
5	22.86672	92.76907
6	22.86668	92.76934
7	22.86687	92.78023
8	22.86541	92.78332
9	22.86126	92.78671
10	22.86168	92.78642
11	22.85428	92.79023
12	22.84853	92.79537
13	22.84619	92.7971
14	22.84608	92.79644
15	22.84389	92.79636
16	22.84166	92.79585
17	22.84052	92.79304
18	22.853	92.79958
19	22.84806	92.80173
20	22.84773	92.81734

Table 4.1 (A)

Sl.No	Latitude	Longitude
21	22.85279	92.8157
22	22.85322	92.8158
23	22.85468	92.81928
24	22.84906	92.80629
25	22.84944	92.80595
26	22.84965	92.80602
27	22.86888	92.76292
28	22.87109	92.75523
29	22.87166	92.75404
30	22.87338	92.75272
31	22.87308	92.75273
32	22.87972	92.7523
33	22.87602	92.75162
34	22.8773	92.7505
35	22.88074	92.74904
36	22.90326	92.75737
37	22.90473	92.761
38	22.90443	92.76069
39	22.9026	92.75834
40	22.89819	92.75427

Table 4.1 (B)

Sl.No	Latitude	Longitude
41	22.89773	92.75388
42	22.89746	92.75398
43	22.89741	92.75405
44	22.89681	92.7532
45	22.89625	92.75269
46	22.89617	92.7508
47	22.898	92.75263
48	22.89428	92.74573
49	22.89709	92.74737
50	22.89734	92.74773
51	22.8976	92.74788
52	22.89524	92.74517
53	22.89567	92.74547
54	22.89374	92.7469
55	22.89552	92.74772
56	22.89303	92.744
57	22.89301	92.74345
58	22.89351	92.74094
59	22.89036	92.73975
60	22.89083	92.73988
61	22.89086	92.73922
62	22.88905	92.73966
63	22.887	92.73986
64	22.89037	92.73912
65	22.88998	92.74467
66	22.89041	92.74579
67	22.88527	92.74777
68	22.88088	92.75206
69	22.87655	92.75309
70	22.87702	92.75128
71	22.91271	92.75494
72	22.93795	92.74635
73	22.93862	92.7456
74	22.93962	92.74505
75	22.92471	92.74017
76	22.95093	92.73891

Table 4.1 (C)

77	22.95526	92.73966
78	22.96073	92.74028
79	22.96109	92.74004
80	22.96171	92.73951
81	22.9627	92.73872
82	22.96519	92.7353
83	22.96527	92.73246
84	22.96545	92.73185
85	22.9665	92.73091
86	22.96818	92.7296
87	22.97261	92.7294
88	22.97333	92.72852
89	22.97418	92.72565
90	22.9754	92.72496
91	22.98109	92.72442
92	22.98658	92.72455
93	22.99133	92.72379
94	23.00346	92.72285
95	22.88618	92.73644
96	22.88582	92.7319
97	22.88674	92.73091
98	22.88708	92.73033
99	22.88735	92.73006
100	22.88772	92.7295
101	22.88945	92.72823
102	22.88982	92.72793
103	22.89014	92.72717
104	22.89092	92.72766
105	22.89205	92.727
106	22.89258	92.7264
107	22.89457	92.7252
108	22.89972	92.72128
109	22.908	92.71873
110	22.90818	92.71816
111	22.90898	92.71845
112	22.91202	92.71729
113	22.91736	92.71412
114	22.92081	92.71116
115	22.88324	92.73698
116	22.88333	92.7328
117	22.88359	92.73177
118	22.9423	92.76859
119	22.87	92.757
120	22.86726	92.763

Table 4.1 (D)

121	22.866	92.76
122	22.864	92.758
123	22.866	92.757
124	22.869	92.756
125	22.871	92.753
126	22.876	92.75
127	22.884	92.742
128	22.86	92.757
129	22.85994	92.75798
130	22.86137	92.75766
131	22.85447	92.82412
132	22.85606	92.82371
133	22.85843	92.82737
134	22.8613	92.82869
135	22.86576	92.8276
136	22.86164	92.82968
137	22.85333	92.82012
138	22.83663	92.79908
139	22.83693	92.8021
140	22.83659	92.80371
141	22.8277	92.80547
142	22.83982	92.79596
143	22.86251	92.78859
144	22.86833	92.76267
145	22.86884	92.76184
146	22.87027	92.7597
147	22.87288	92.75924
148	22.91244	92.75744
149	22.93301	92.75732
150	22.883	92.721
151	22.87	92.715
152	22.872	92.715

Table 4.1 (E)

4.3. Laboratory Data

4.3.1. Thematic Maps : Thematic layers forms an important data in order to prepare the landslide susceptibility map. In this study various thematic maps viz., slope map, drainage density and distance to drainage map which were derived from the drainage map, lithology map, structure map, plan curvature map and landuse landcover were prepared.

4.3.1.1 Slope :

Slope derived from DEM using Spatial Analyst in ArcGIS varies from 0 to 73° and has been categorised into five classes from 0 to 5°, 5 to 15°,15 to 25°, 25 to 35° and higher than 35°. Slopes more than 35° has lesser spatial extent forming 10.5% of the area and all slopes higher than 35° is classified as a single class. The slope map shows that slope ranging from 15 to 25° constitute about 37% of the area. Low slope angles are found in the areas where fourth order streams flow.

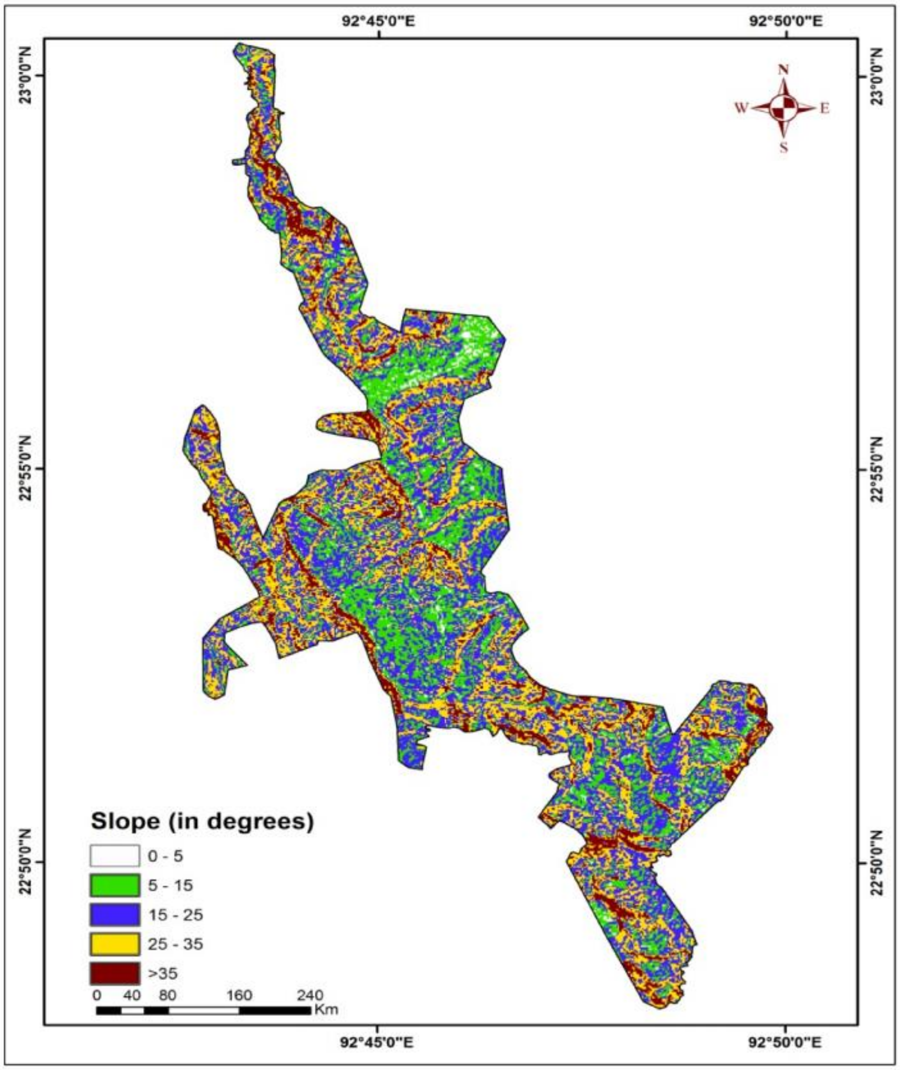


Fig. 4.2: Slope map

4.3.1.2. Plan Curvature

Plan curvature also known as planform curvature is the curvature perpendicular to the direction of slope. A positive value indicates that the surface is sidewardly convex and negative value indicates that the surface is concave. . The plan curvature of the study area is prepared using spatial analyst Fig.4.2. The curvature values range from -14.87 to 20.31m/100 m and areas with flat curvature -0.41 to 0.37 m/100m a range close to zero form the dominant type due to the peneplained nature of the terrain High negative values are found in the areas where 1st and 2nd order streams die to high erosion. Flat curvature is noticed along the course of 3rd order to higher order streams and also on hill tops.

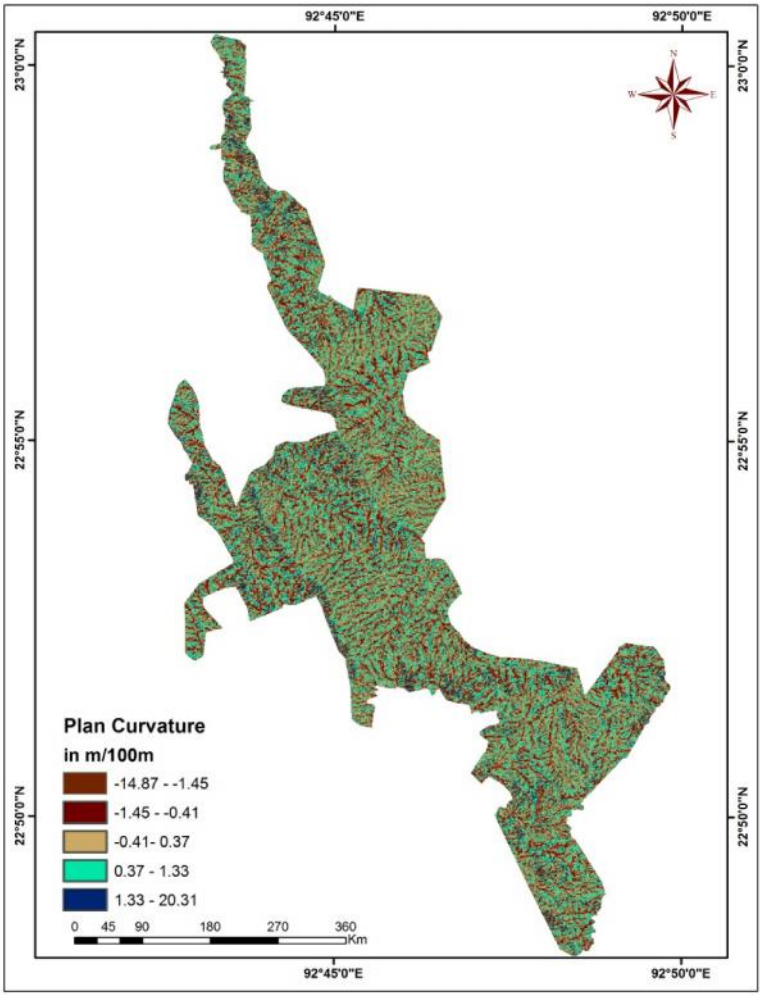


Fig.4.3: Plan curvature Map

4.3.1.3. Drainage derivatives :

Streams play a major role in landslide susceptibility. They can effectively let the water flow from the catchment area controlling the soil saturation which alters the shear stress of the soil. Water flowing downstream at steep slopes can transport the unconsolidated material forming debris flow. The streams during floods can undermine the banks of the rivers removing the lateral support inducing landslides even in low slopes. The work of drainage hence is complex as they influence the stability by toe erosion or by saturating the slope material or both (Mathew et al., 2007).

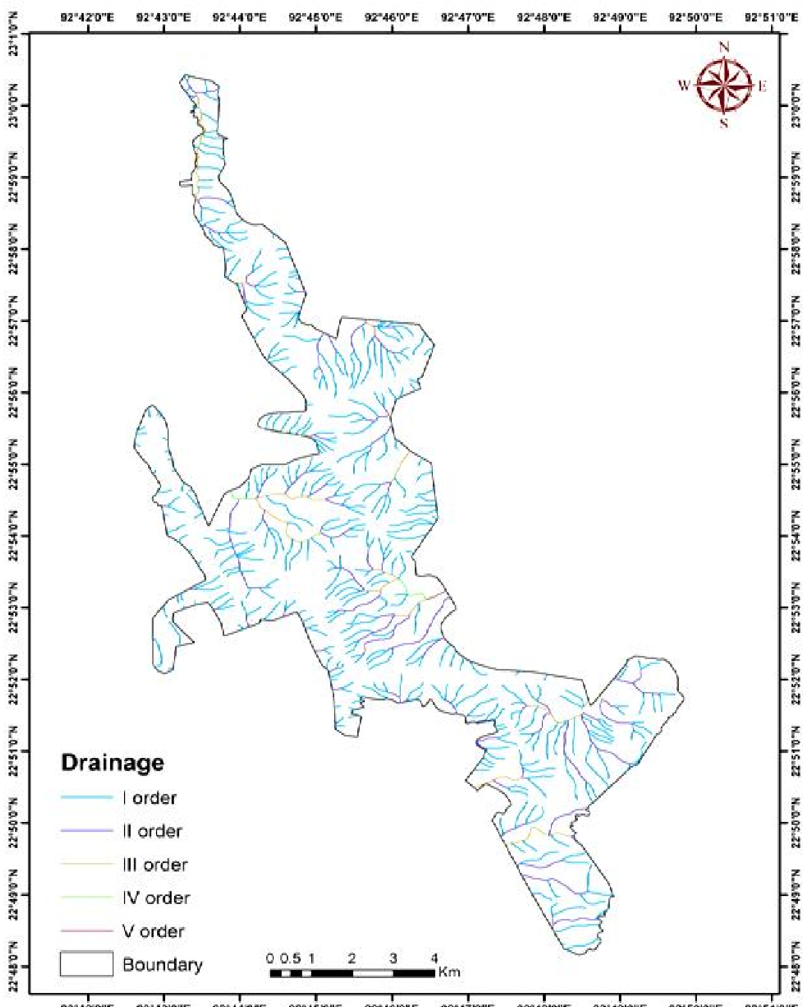


Fig. 4.4 : Drainage Map

In landslide susceptibility Zonation two characteristics of the streams are considered as causative factors. One is drainage density, which is defined as the cumulative length of the streams per unit area. It provides a measure of groundwater infiltration and surface runoff. Low drainage density is normally unfavourable for slope stability as infiltration is more and the slope stability of the region is reduced (Sarkar and Kununga, 2004). The other causative factor is distance to drainage which is responsible for toe erosion which causes slope failures (Mathew et al., 2007).

The drainage density layer is created using the line density tool in Spatial Analyst of ArcGIS (Fig.4.3). The figure shows that drainage density ranges from 0 to 7.84 with a mean of 4.17 km/km^2.

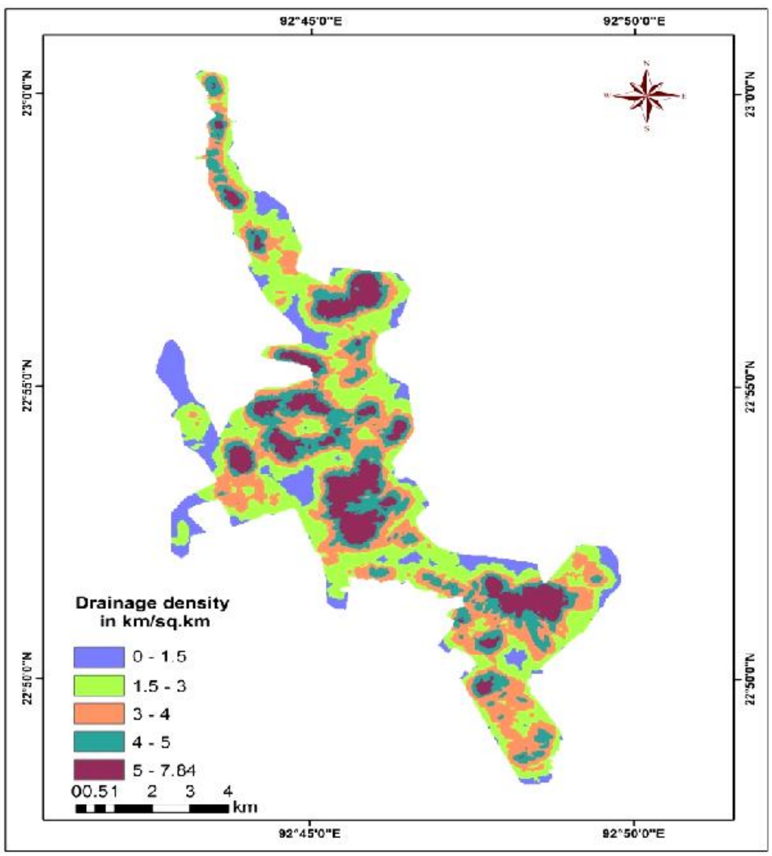


Fig.4.5: Drainage density map

The distance to drainage layer was created by Multiple buffer tool at 50 m interval (fig.4.6). The maximum value of 500 m is set such that no pixel has no-data. Distance to drainage has been used by a number of researchers (Van Westen and Bonilla, 1990; Anbalagan, 1992; Pachauri and Pant, 1992; Donati and Turrini, 2002, Ercanoglu and Lee 2005). Studies made by Akgun and Bulut (2007) have shown that the rate of landslides decrease as the distance from stream increases (Akgun *et al.*, 2008; Lee and Talib, 2005).

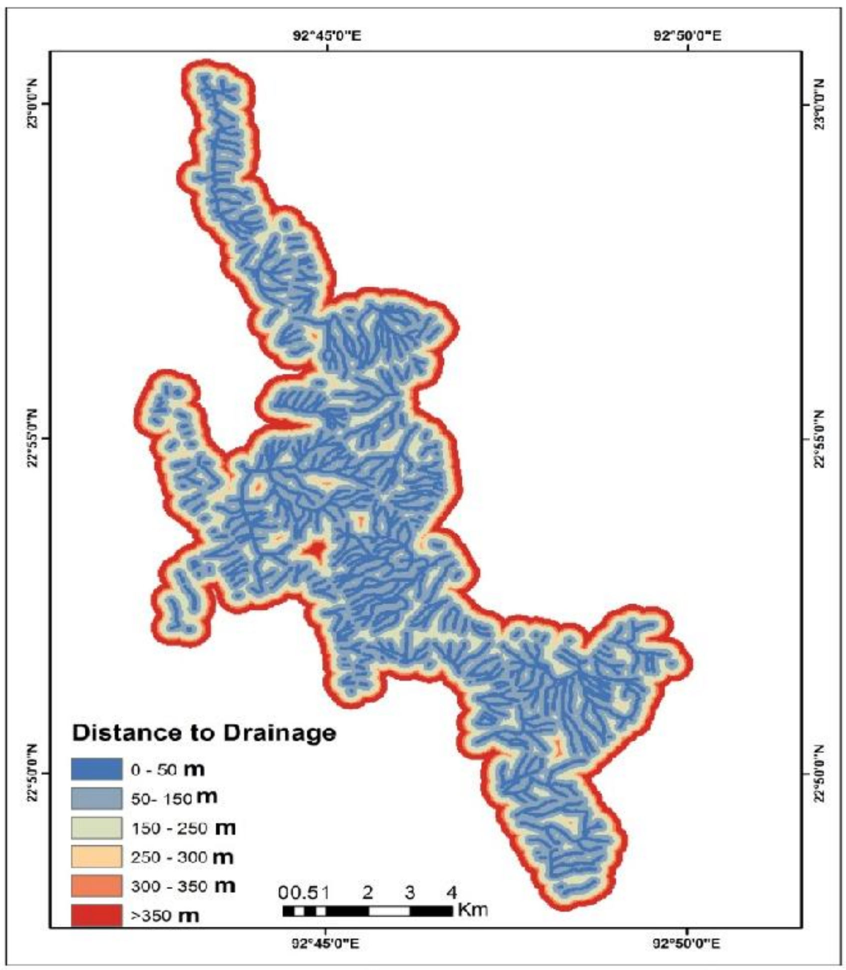


Fig.4.6: Distance to drainage map

4.3.1.4. Landuse/Landcover:

Remote sensing provides synoptic view and multi-temporal data for land use and land cover mapping. Land cover take account of natural features like, water, snow, grassland, forest, and Soil and land use take account of agricultural land, built up land, canal, and other manmade features (Chavare Subhash, 2015). Landuse and Land Cover map was prepared using the worldview data (2019) and was verified with Google Earth. The Google Earth image can be integrated with the layers in GIS which enabled the digitisation of landuse boundary more accurately. Landuse is an important factor in landslide susceptibility zonation (Anbalagan, 1992). Generally areas with thick vegetation are less susceptible to landslide as the roots of the trees hold the unconsolidated material preventing their sliding. Alternatively normalised vegetation index (NDVI) calculated by using the formula NDVI = (IR – R)/(IR + R), where IR value is the infrared portion and R – value is the red portion of the electromagnetic spectrum (Lee and Talib, 2005). However, the NDVI is not effective as settlements are not taken into account and settlement areas are prone to landslides as the natural slope is steepened by human activities. The landuse/landcover map prepared is shown in Fig. 4.7 and the units recognised in the areas are 1) Agricultural plantation where vegetable crops are grown, 2) Jhumland/cultivated land, 3) Less Dense Forest with lesser vegetation when compared with dense forests, 4) Open Forest which are forests with space vegetation 5) Builtup/settlements and 6) Scrubland. Open forest form the most extensive landuse in the area.

4.3.1.5. Lithology

Lithology includes the composition, fabric, texture or other attributes that influence the physical or chemical behavior of rocks and engineering soils. These attributes are very important in determining the shear strength, permeability, susceptibility to chemical and physical weathering, and other characteristics of soil and rock materials, which in turn affect the slope stability (Varnes, 1984). The lithology present in this area are Shale-sandstone, shale-siltstone, siltstone-shale of middle bhuban, sandstone of upper bhuban, crumpled shale of middle bhuban and gravel, sand,sild and clay as shown in fig.4.8

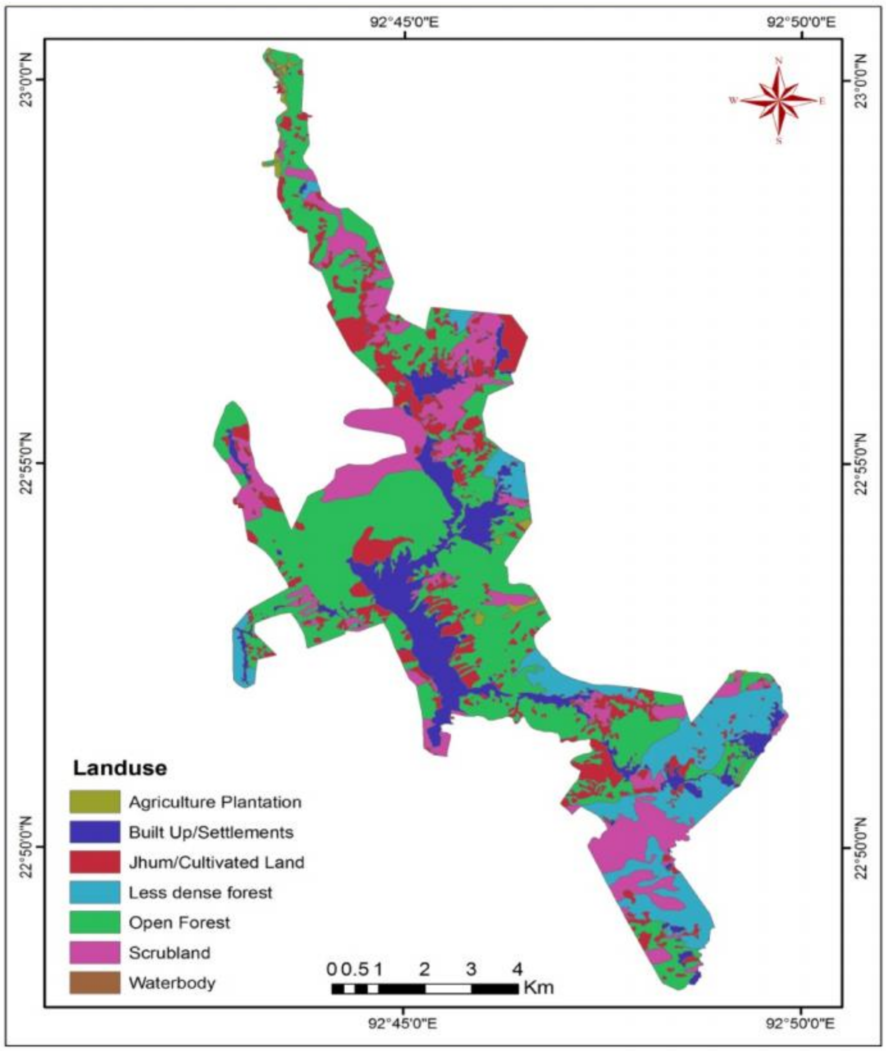


Fig. 4.7: Landuse/landcover map

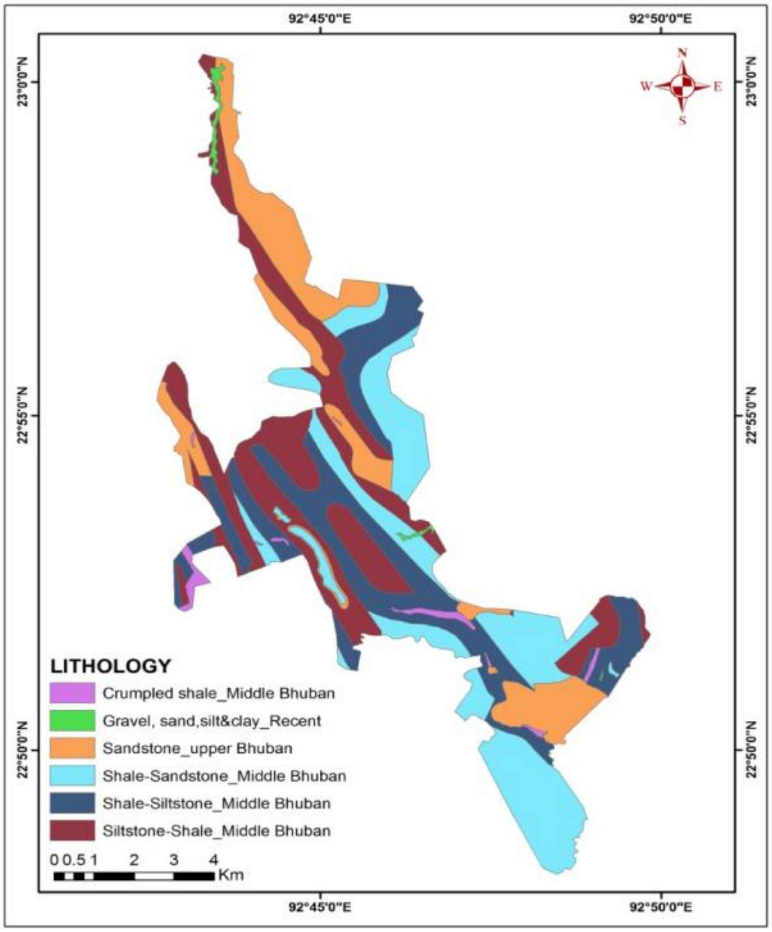


Fig. 4.8: Lithology map

4.3.1.6. Structure

Structure includes the features of inhomogeneity and discontinuity in rocks or soils, at scales larger than a hand specimen, including stratigraphic sequence, attitude of layering, gross changes in lithology, bedding planes, joints, faults and folds. (Varnes, 1984). According to Ramakrishnan et al. 2013 Geological structures such as fractures, rock cleavages, and faults play a vital role in building the pore pressure . Hence, from high-resolution satellite imagery, numerous planes of weakness were interpreted as lineaments. It was observed that the rocks exposed within the study area were traversed by several faults and fractures of varying magnitude and length (MIRSAC, 2006). Areas located close to the geological structures like faults zones and other geological structures are considered to be more vulnerable to landslides. The geological structures present in thestudy are shown in Fig. 4.9 below.

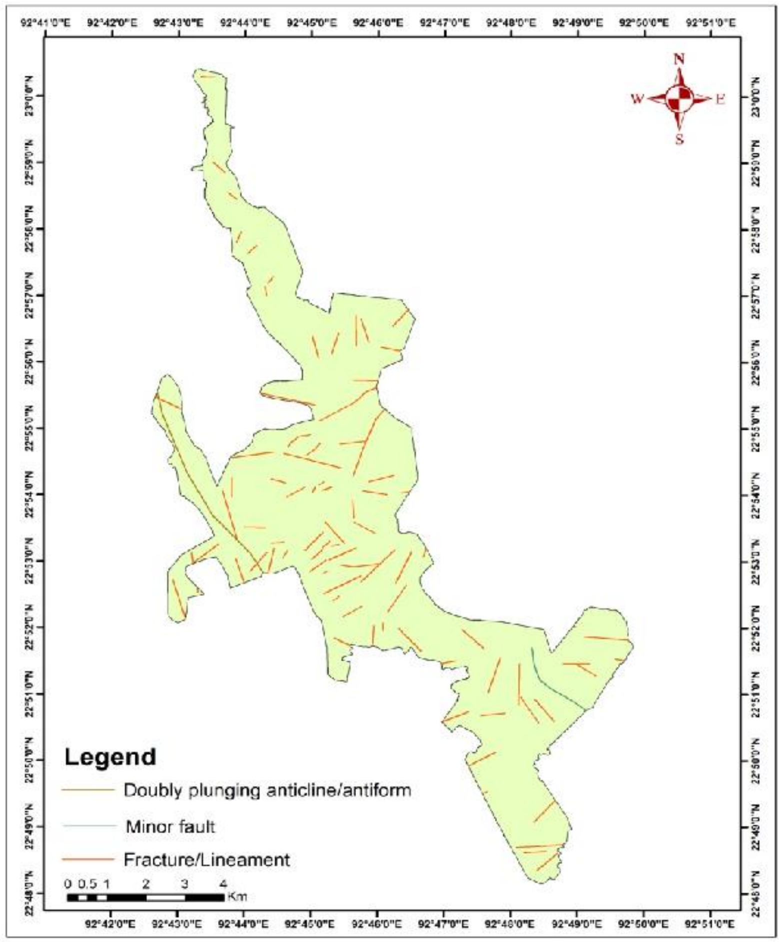


Fig. 4.9:Geological Structure map

4.4. Rainfall:

Monthly and daily rainfall report of the study area was collected. This data was collected from Directorate of Agriculture and Directorate of Economics and statistics, Government of Mizoram. From the collected data we can clearly assume that rainfall record is highest in the month of July for the past 20 years in the study area. It can also infer that rainfalls during May, June, July, August and September are higher as compared to other month of the year as shown in the table below.

Table 4.1(A): Monthly rainfall record of Lunglei from 1999 to 2019 (source:Directorate of Agriculture, Govt. Of India)

YEAR	Jan	Feb	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.	TOTAL
1999			20	17	436	775	734	598	692	395	-	98	3763
2000	6	5	162	289	918	1008	866	1412	501	290	97	-	5554
2001	Nil	8	8	49	617	784	613	521	426	375	240	Nil	2614
2002	24	Nil	77	70	738	530	981	543	312	89	141	Nil	3505
2003	Nil	1	25	58	220	1196	477	624	584	170	Nil	27	3382
2004	-	-	25	290	296	1233	919	535	594	173	11	-	4076
2005	2	-	87.1	104.8	267.6	271.9	556.2	622.2	436.3	412.6	-	12.8	2773.5
2006	-	-	-	33	485	704	349	193	212	235	-	-	3211.9
2007	-	55.2	1.8	173.6	454.5	701.9	804.2	910.7	945.4	317.1	73	-	4437.4
2008	72	8.1	29.3	-	-	-	-	-	-	-	-	-	109.4
2009	-	-	-	-	-	-	-	830.2	482.4	198.2	169.1	-	1679.9
2010	-	85.8	-	-	-	-	-	-	-	-	-	-	86.8
2011	-	-	-	55.4	607.9	574	495	749.3	489.5	192.9	-	-	3164
2012	-	5	17	338	278	903	-	1121	508	529	124	-	3822
2013	-	5	-	147.3	841	823.9	689.2	826.3	597.8	221.2	-	-	4151.7
2014	-	44.8	15	20.3	320	381	330	520.3	687	142.8	12	12	2485.2
2015	27.2	-	38.9	170.8	93.8	525.3	714.8	668.3	609.3	220	12	-	3080.4
2016	5	29	49	23	308.9	670.6	465.2	426	483.7	176.6	85	-	2722
2017	0	0	103	290.4	173.9	518	533	599.4	497.8	259.8	25.1	38.4	3039.2
2018	14.4	-	23.4	124.4	175.8	685.1	374.1	347.3	189.7	207.1	13	25.6	
2019	0	67.1	57.9	86.3	174.5	364.4	727.3	328.4	238.8	75.6	54.1	12.3	

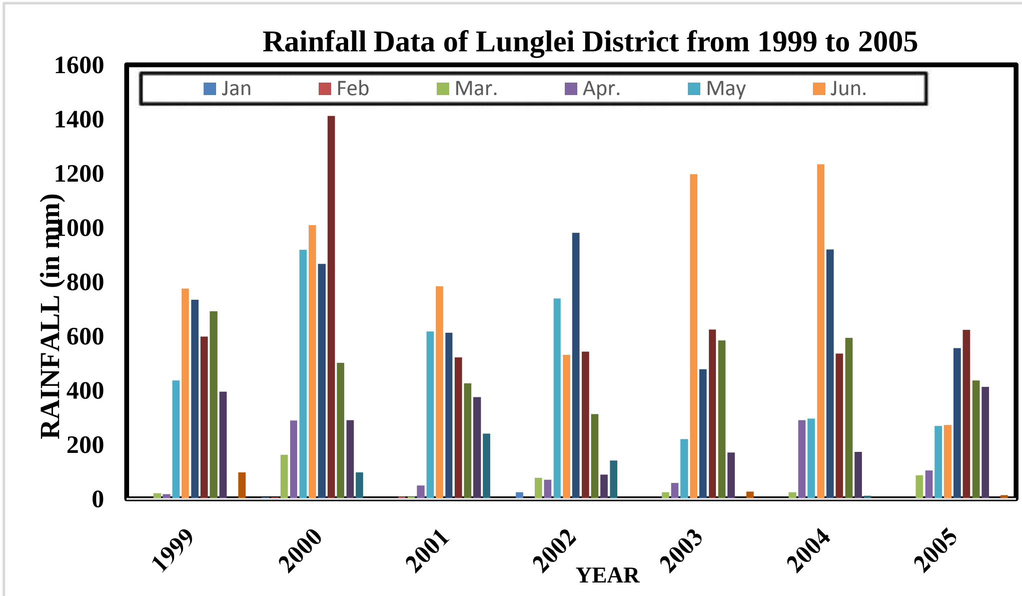


Fig. 4.10(a) : Rainfall data (1999 – 2005)

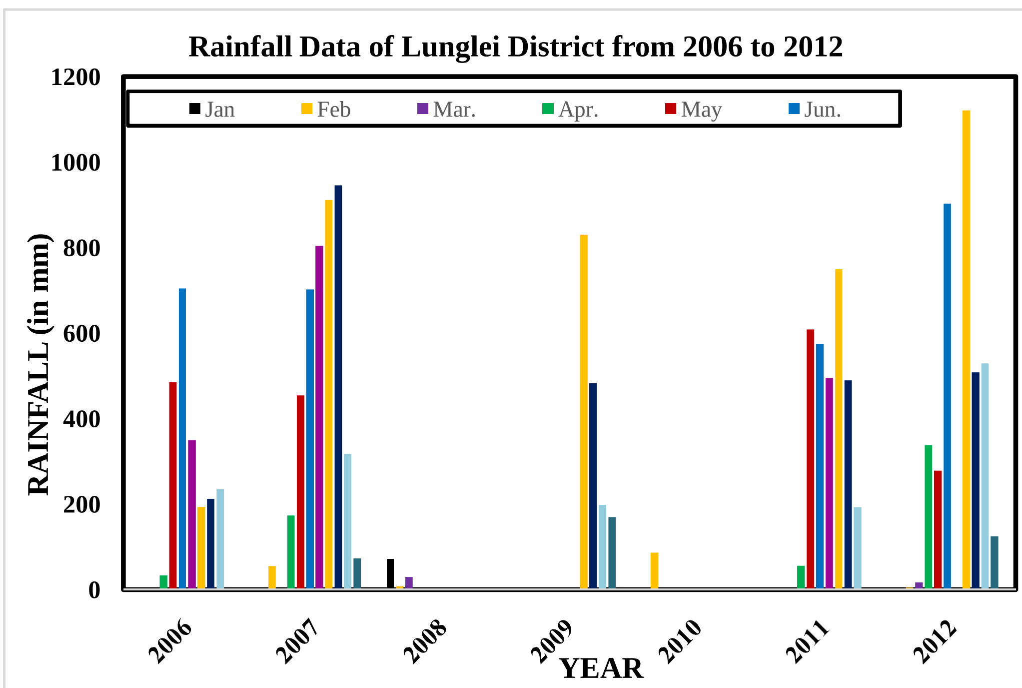


Fig. 4.10(b) : Rainfall data (2006 – 2012)

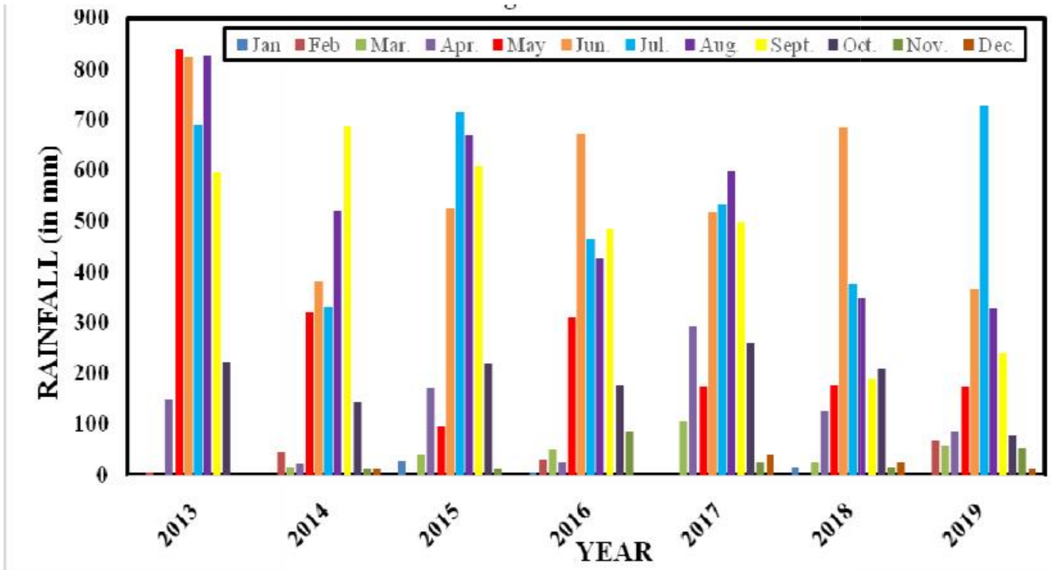


Fig.4.10(c): Rainfall data (2013 – 2019)

4.5. FREQUENCY RATIO METHOD: THE RELATIONSHIP BETWEEN LANDSLIDES AND FACTORS

The causative factors selected for generating the LSM, such as the slope, drainage density, distance to drainage, lithology, curvature, landuse, structure and lithology were assessed using the frequency ratio method to find out the relationship between the location of the landslides in the study area and these factors. Probabilistic approaches are based on the observed relationships between each factor and the distribution of landslides.(Lee and Talib 2005)

4.5.1 RELATIONSHIP BETWEEN LANDSLIDE OCCURENCE AND SLOPE

Slope is classified into five categories viz., 0-5°, 5-15°, 15-25°, 25-35° and >35°. In the case of the relationship between landslide occurrence and slope, only 1 landslide occur below a slope of 5°. It is found that majority of the landslides falls in the category of 15°-25°. Below the slope of 15°, the frequency ratio was less than 1, which indicates a very low probability of landslide occurrence of 0.793.

For slopes above 15°, the ratio was more than 1, which indicates a high probability of landslide occurrence. This means that the landslide probability increases according to slope angle. As the slope angle increases, then the shear stress in the soil or other unconsolidated material generally increases. Gentle slopes are expected to have a low frequency of landslides because of the generally lower shear stresses associated with low gradients. Steep natural slopes resulting from outcropping bedrock, however, may not be susceptible to shallow landslides.(Lee and Talib, 2005). Steep natural slopes resulting from outcropping bedrock, however, may not be susceptible to shallow landslides.(Lee and Pradhan, 2006)

From the calculation of frequency ratio, class intervals of 15- 25° is maximum with 45 landslides out of 114 slides which is 39.47%. The landslide percentage of 39.47 is divided by the percentage of the class which is 37.007 to calculate the frequency ratio which is 1.066. Similarly the frequency ratios for the other classes are calculated. The frequency ratios for the different classes of slope used in the study are given in Table 4.2.

Table 4.2. Frequency ratio of Landslide occurrences based on Slope

Factor	Class	Landslides Occurrence points	Landslides Occurrence Points(%)	Pixel In domain	Pixel In Domain(%)	Frequency Ratio
Slope	0-5°	1	0.877193	1701	2.291063	0.382876
	5-15°	21	18.42105	17233	23.21099	0.793635
	15-25°	45	39.47368	27476	37.00721	1.066649
	25-35°	35	30.70175	19721	26.56206	1.15585
	>35°	12	10.52632	8114	10.92868	0.963183

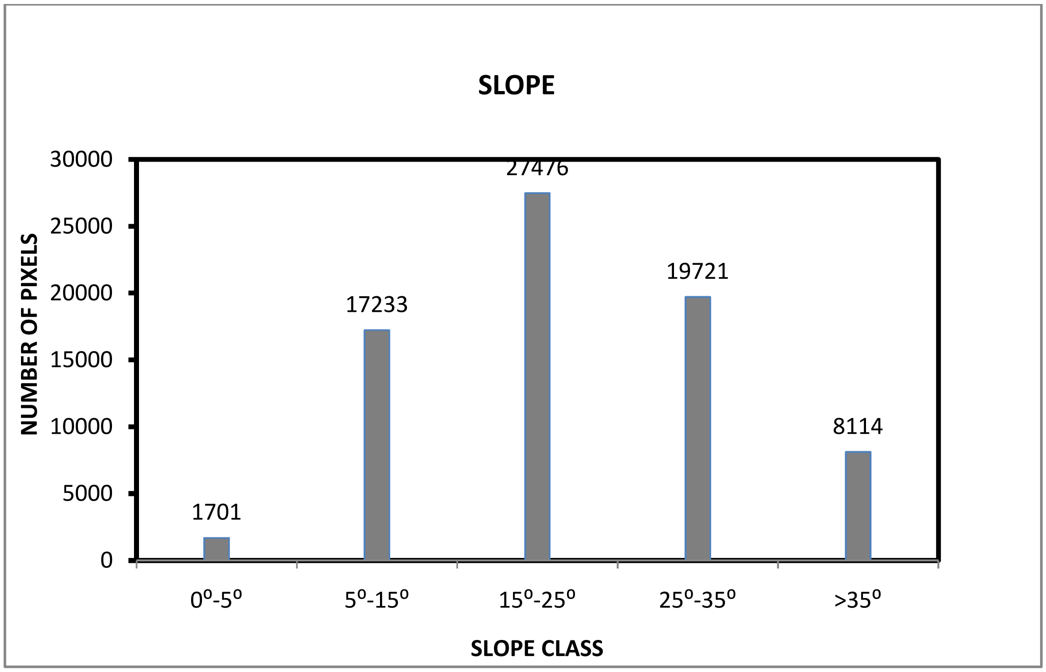


Fig 4.11 : Number of pixels in each slope class

4.5.2 RELATIONSHIP BETWEEN LANDSLIDE OCCURENCE AND DRAINAGE DENSITY

In the case of the relationship between landslide occurrence and drainage density, the drainage density ranges from 0 to 7.84 km/km^2 and is classified into five classes viz., 0-1.5 km/km^2, 1.5-3km/km^2, 3-4km/km^2, 4-5km/km^2, 5-7.84 km/km^2 based on Natural Breaks (Jenk's) method. The percentage of landslides in general decrease with increasing drainage density (Table.4.3). The frequency ratio shows that highest ratio is found in areas with a drainage density of 1.5-3km/km^2, followed by 0-1.5 km/km^2. The drainage density is an important factor as rain water percolates in areas with low drainage density increasing the hydrostatic pressure which alters the strength of the soil overburden.

Table 4.3. Frequency ratio of Landslide occurrences based on Drainage density.

Factor	Class (km/km^2)	Landslides Occurrence points	Landslides Occurrence Points(%)	Pixel In domain	Pixel In Domain (%)	Frequency Ratio
Drainage Density	0 - 1.5	16	14.03509	8580	11.56599	1.213479
	1.5 - 3	48	42.10526	23952	32.28772	1.304064
	3 - 4	30	26.31579	19413	26.16907	1.005607
	4 - 5	17	14.91228	12987	17.50671	0.851804
	5 - 7.84	3	2.631579	9251	12.47051	0.211024

The drainage density layer has been classified into 5 sub classes based on Natural breaks (Jenks) method, here very low drainage density 0-1.5 covering 8580 pixels, low drainage density(1.5-3) covering 23952 pixels, moderate drainage density covering 19413 pixels, high drainage density covering 12987 pixels and very high drainage density covering 9251 pixels in the study area of 17974 pixels.

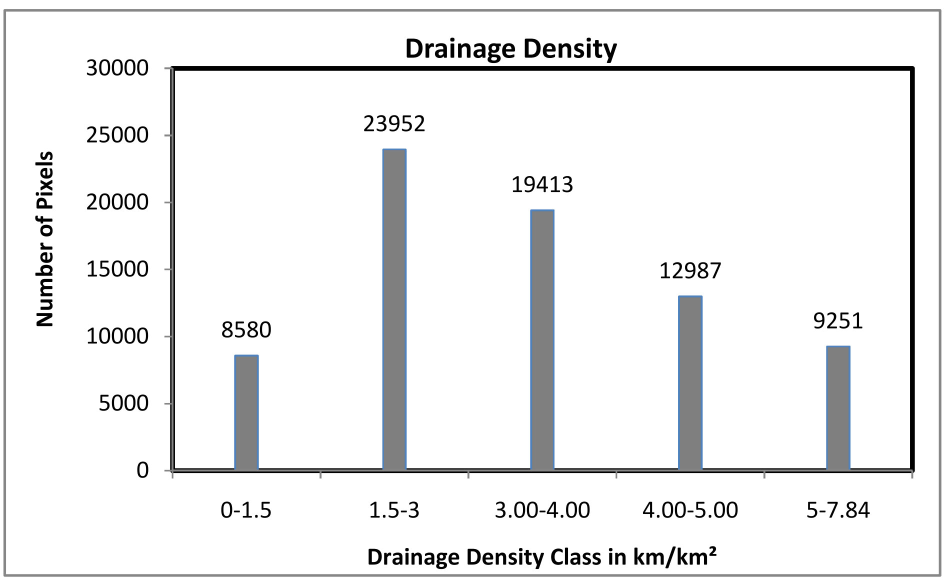


Fig 4.12 : Number of pixels in each Drainage density class.

4.5.3 RELATIONSHIP BETWEEN LANDSLIDE OCCURENCE AND DISTANCE TO DRAINAGE

In order to assess the influence of drainage lines on landslide occurrence, the drainage lines were identified by buffering using the multiple ring buffer tool . It can be seen from the Table 4.4 that as the landslide frequency decreases as the distance from a drainage line increases. Majority of the landslides (85.96%) in the area have been occurred close to the stream within a distance of 150 m and only 15 landslides have occurred between distance 150 to 250m , only 1 landslide has taken place between 250 m and 300 m, and no landslide had taken place beyond 300m. Hence, distance to drainage taken as basis for landslide hazard zonation, this is due to the fact that the landslides are due to the creation of steep slope due to erosion. From the frequency ratio (Table 4.4) it is evident that 85.96% of the landslides have occurred within a distance of 150 m from the drainage and hence the factor can be effectively used.

Table 4.4. Frequency ratio of Landslide occurrences based on Distance to drainage

Factor	Class (km/km^2)	Landslides Occurrence points	Landslides Occurrence Points(%)	Pixel In domain	Pixel In Domain(%)	Frequency Ratio
Distance to Drainage	0-50	51	44.73684	27887	23.89058	1.872572
	50-150	47	41.22807	43040	36.87204	1.118139
	150-250	15	13.15789	19372	16.59585	0.792843
	250-300	1	0.877193	6290	5.388596	0.162787
	300-350	0	0	5472	4.687821	0
	>350	0	0	14667	12.56511	0

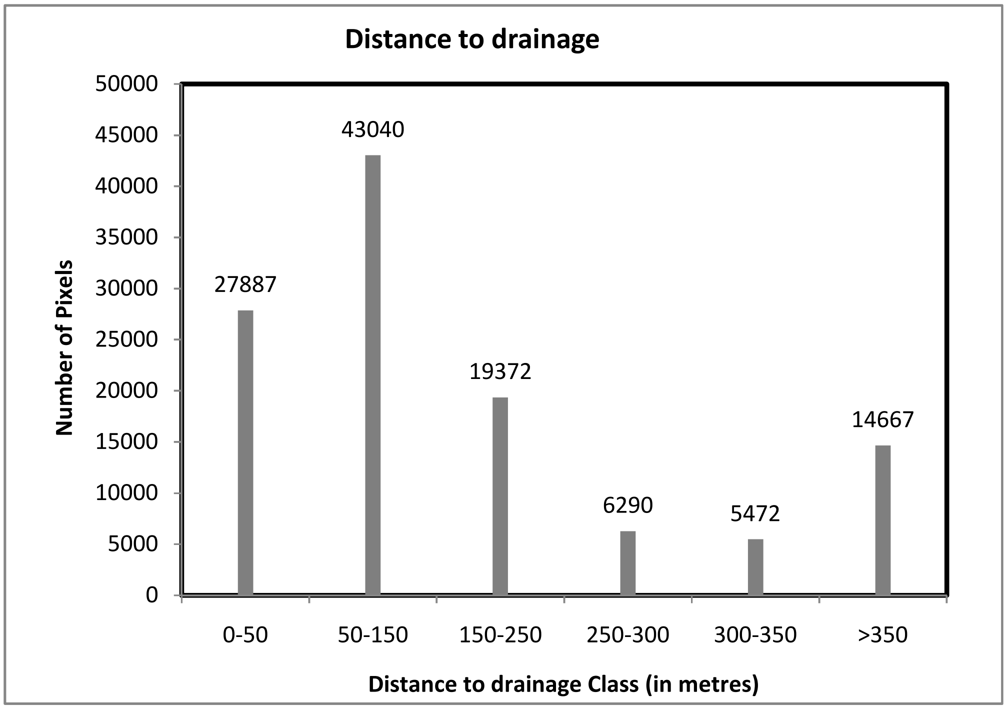


Fig 4.13 : Number of pixels in each Distance to Drainage classes

The distance to drainage layer has been categorised into 6 sub variables namely 0-50 m covering 27887 pixels which is the highest, 50-150 m covering 43040 pixels, 150-250 m covering 19372 pixels, 250-300 m covering 6290 pixels and 300-350 m covering 5472 pixels, >350 m covering 14667 pixels. The 0-50 m sub variable, covers 44.73% of the total landslide followed by 50-150 m which cover 41.22% of the landslides (Table 4.4).

4.5.4 RELATIONSHIP BETWEEN LANDSLIDE OCCURENCE AND LANDUSE/LANDCOVER

Due to increased human activities and extensive deforestation the stability of slopes is often reduced. It can be clearly observed that the urban activities let to the modification of slope for widening of road and leveling of the terrain forming steep cut. As a result the landslide frequency was very high for the settlement where most of the road network occurs. The landuse/landcover factor has been classified as Agriculture plantation, jhum/cultivated land, built up/settlements, scrubland, less dense forest and open forest. The frequency ratio for landslides calculated for landuse factor is given in (Table 4.6). The calculated frequency ratio for the area shows that areas with built up/settlement shows high frequency ratio of 1.915 as the construction activity invariably results in slope steepening consequent to the leveling of the housing plots for construction activity. Only 1 landslide falls on the agricultural plantation even though they are more at higher risk to landslide, this may due to the reason that the soils are often tilled for the airing of plants roots and also the slope where the plants are grown are quite gentle, so farmers does not report much landslides in these area as they quickly level the ground to continue their agricultural plantations. From the Table 4.5. less dense forest shows lesser frequency ratio as the vegetation is thick in these areas compared to other landuse classes. The areas are less disturbed and the roots of the trees hold the soil together and are least vulnerable to landslides. The frequency ratios calculated for different landuse classses show that less dense forest and waterbody shows minimum frequency ratio followed by open forest and scrubland. However, settlements, plantations and jhum land have higher prababilty of slope instability.

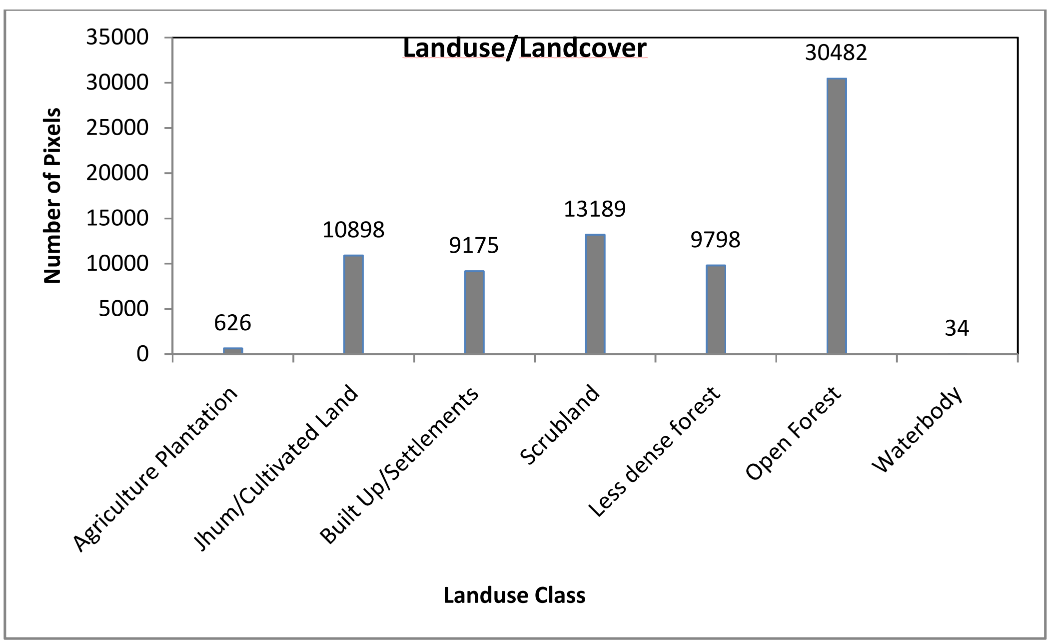


Fig 4.14 : Number of pixels in each Landuse/landcover classes

Table 4.5. Frequency ratio of Landslide occurrences based on Landuse/landcover

Factor	Class (km/km^2)	Landslides Occurrence points	Landslides Occurrence Points(%)	Pixel In domain	Pixel In Domain(%)	Frequency Ratio
Landuse/ landcover	Agriculture Plantation	1	0.877193	626	0.843643	1.039768
	Jhum/ Cultivated Land	18	15.78947	10898	14.68694	1.075069
	Built Up/ Settlements	27	23.68421	9175	12.3649	1.91544
	Scrubland	19	16.66667	13189	17.77445	0.937675
	Less dense forest	6	5.263158	9798	13.2045	0.398588
	Open Forest	43	37.7193	30482	41.07976	0.918197
	Water body	0	0	34	0.045821	0

4.5.5. RELATIONSHIP BETWEEN LANDSLIDE OCCURENCE AND PLAN CURVATURE

The plan curvature values range from -14.87 to 20.31m/100 m and areas with flat curvature -0.41 to 0.37 m/100m a range close to zero form the dominant type due to the peneplained nature of the terrain. High negative values are found in the areas where 1st and 2nd order streams die to high erosion. The frequency ratio shows that highest ratio is found in areas with a plan curvature of -0.41 to 0.37 m/100m which is 1.200 and the lowest ratio which is 0.431 is found in classes -14.87 – 1.45m/100m. Only 2 and 3 landslides occur in classes between -14.87 – 1.45m/100m and 1.33 to 20.31m/100m respectively and 31 landslides occur in classes between -1.45 to -0.41m/100m and 28 landslides occur in classes between 0.37 to 1.33m/100m.

Table 4.6. Frequency ratio of Landslide occurrences based on Plan Curvature

Factor	Class (km/km^2)	Landslides Occurrence points	Landslides Occurrence Points(%)	Pixel In domain	Pixel In Domain(%)	Frequency Ratio
Plan Curvature	-14.87 to 1.45	2	1.754386	17390	4.066723	0.4314
	-1.45 to -0.41	31	27.19298	115016	26.89697	1.011006
	-0.41 to 0.37	50	43.85965	156258	36.54158	1.200267
	0.37 to 1.33	28	24.5614	117620	27.50592	0.89295
	1.33 to 20.31	3	2.631579	21333	4.98881	0.527496

4.5.6 RELATIONSHIP BETWEEN LANDSLIDE OCCURENCE AND STRUCTURE

The density of structure was classified into five classes viz. very low, low, moderate, high and very high. 31 landslides occurs on classes very low covering 22164 pixels, low classes covers 15906 with 26 landslides, moderate class covering 17267 pixels in which 28 landslides occur, high covers 12978 pixels and very high covers lowest pixels ie. 5574 with 11 landslides occur in this class. The frequency ratio value is highest in classes very high.

Table 4.7. Frequency ratio of Landslide occurrences based on Structure

Factor	Class	Landslides Occurrence points	Landslides Occurrence Points(%)	Pixel In domain	Pixel In Domain(%)	Frequency Ratio
Structure	Very low	31	27.19298	22164	29.99635	0.906543
	Low	26	22.80702	15906	21.52688	1.059467
	Moderate	28	24.5614	17267	23.36884	1.051032
	High	18	15.78947	12978	17.56418	0.898959
	Very high	11	9.649123	5574	7.543748	1.279089

4.5.7 RELATIONSHIP BETWEEN LANDSLIDE OCCURENCE AND LITHOLOGY

The lithology layer has been classified into 6 classes namely Shale-sandstone, shale-siltstone, siltstone-shale of middle bhuban, sandstone of upper bhuban, crumpled shale of middle bhuban and gravel, sand,sild and clay are identified in this area. Out of 114 landslides used for calculating the frequency ratio 7 landslides falls in Shale-sandstone, 46 landslides falls on shale-siltstone which constitute maximum landslides followed by siltstone-shale of middle bhuban with 30 landslides, and 29 landslides falls on sandstone of upper bhuban. Only 1 landslide falls on both the class of Crumpled shale and gravel, sand,silt and clay (Table 4.8). The percentages of landslides are 6.14%, 40.35%, 26.31%, 25.43%, 0.877% and 0.877 respectively. In the relationship between landslide occurrence and lithology, the frequency ratio was highest in shale-siltstone areas with 1.66, and lowest in shale- sandstone areas with 0.213 only.

Table 4.8. Frequency ratio of Landslide occurrences based on Lithology

Factor	Class (km/km^2)	Landslides Occurrence points	Landslides Occurrence Points(%)	Pixel In domain	Pixel In Domain(%)	Frequency Ratio
Lithology	Shale-sandstone	7	6.140351	21342	28.72177	0.213787
	Shale-Siltstone	46	40.35088	18055	24.29817	1.660655
	Siltstone-Shale	30	26.31579	19195	25.83237	1.018714
	Sandstone	29	25.4386	14128	19.01327	1.337939
	Crumpled shale	1	0.877193	1075	1.44672	0.606332
	Gravel,sand, silt&clay-recent	1	0.877193	511	0.687697	1.275552

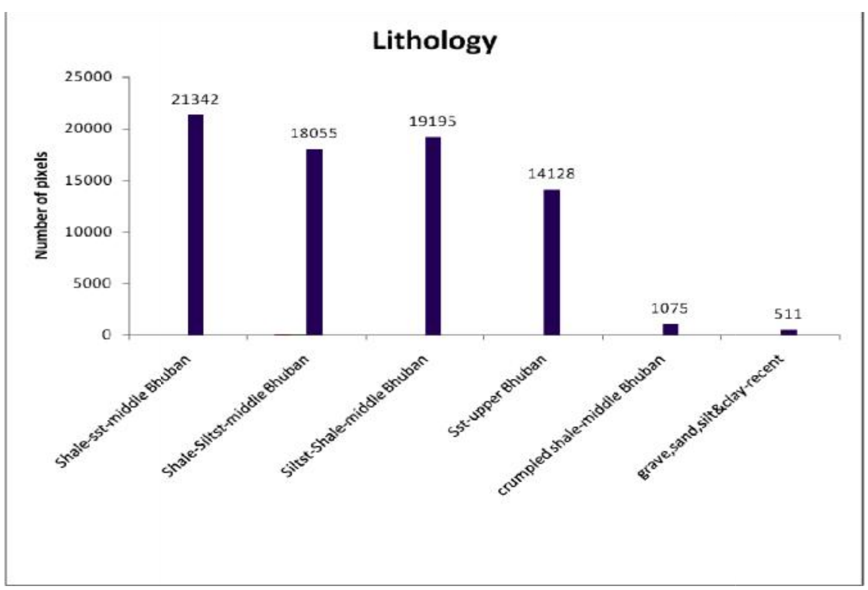
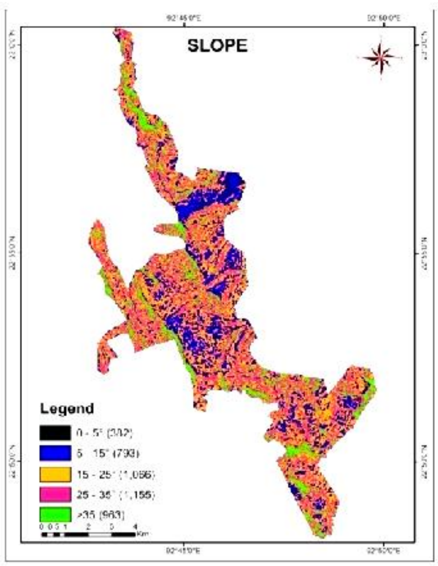
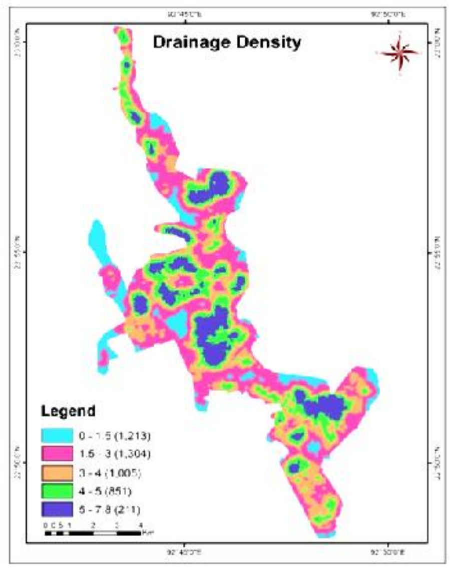


Fig 4.15 : Number of pixels in each Lithology classes

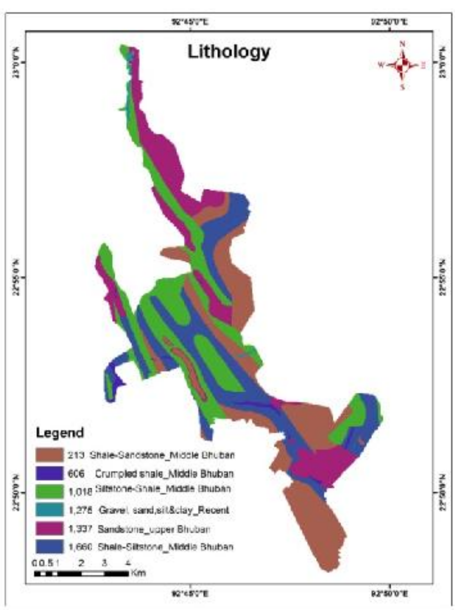
4.6. RECLASSIFICATION : After finding out the frequency ratio, in order to prepare the final landslide susceptibility map, the thematic layers of the causative factors such as slope, drainage density, distance to drainage, landuse/landcover, plan curvature, structure and lithology were again reclassified. This was done by assigning the calculated frequency ratio as new values for each classes using the spatial analyst tool in ArcGIS. The pixel size of the reclassified layers were 30×30m

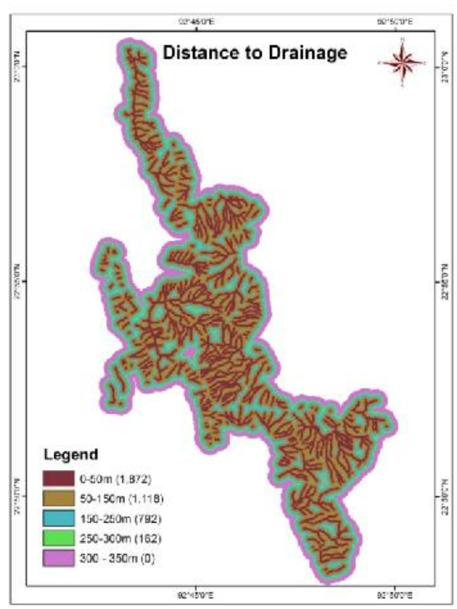


A



B





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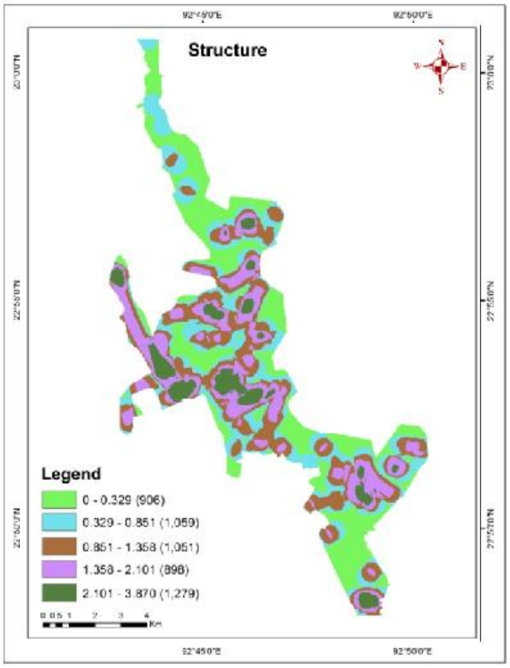

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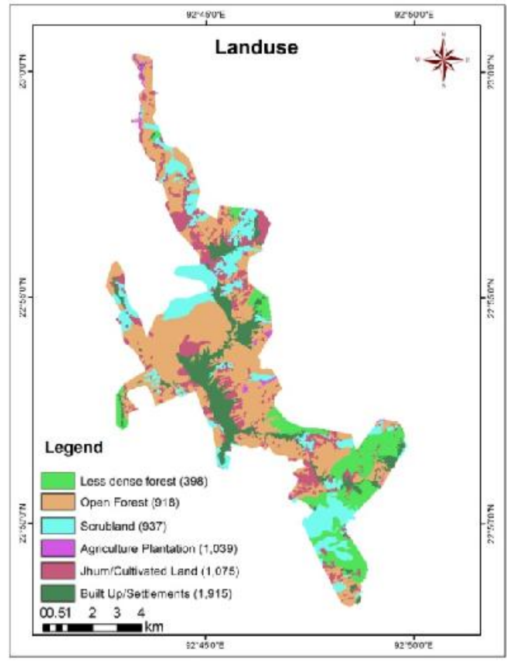

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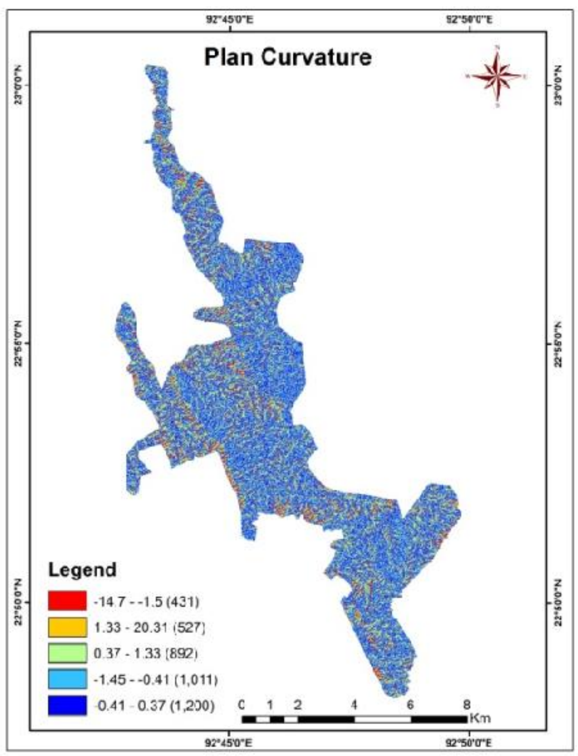

G

Fig.4.16 (A to G) : Reclassified layers using frequency ratio method.

4.7. LANDSLIDE SUSCEPTIBILITY MAPPING:

Using the analysis called weighted sum overlay/overlay analysis in ArcGIS, the Landslide Susceptibility Index (LSI) is generated by adding all the frequency ratio for each pixel.

$$LSI = \Sigma FR$$

where, LSI is the landslide susceptibility index and FR is the frequency ratios of each causative factor.

In order to find out the Landslide Susceptiblity Index (LSI) for each pixel, the thematic layers generated are reclassified using the frequency ratio. In order to make it an integer the FR was multiplied by 1000 and were assigned to the reclassified layers. Overlay analysis was done by using all the 7 causative factors used for landslide susceptibility analysis in spatial analyst extension of ArcGIS. The Landslide susceptibility index varies from 4.009 to 10.296 with a mean of 7.267 and standard deviation of 0.929 after dividing the values in the LSM by 1000. The landslide susceptibility map was classified into five classes such as very low, low, moderate, high and very high and was export in a color coded map as shown in Table 4.17. This LSM generated is based on 114 landslides (75%) out of 152 landslides.

Table. 4.9. Showing number and percentage of landslides, and frequency ratio

Sl. No	Landslide Susceptibility Classes	LS	LS%	Pixels domain	Pixel %	Frequency Ratio
1	Very Low	2	1.754386	7607	10.43656	0.1681
2	Low	7	6.140351	15737	21.59066	0.284398
3	Moderate	20	17.54386	20655	28.338	0.619093
4	High	43	37.7193	18934	25.97684	1.452036
5	Very High	42	36.84211	9955	13.65794	2.697486

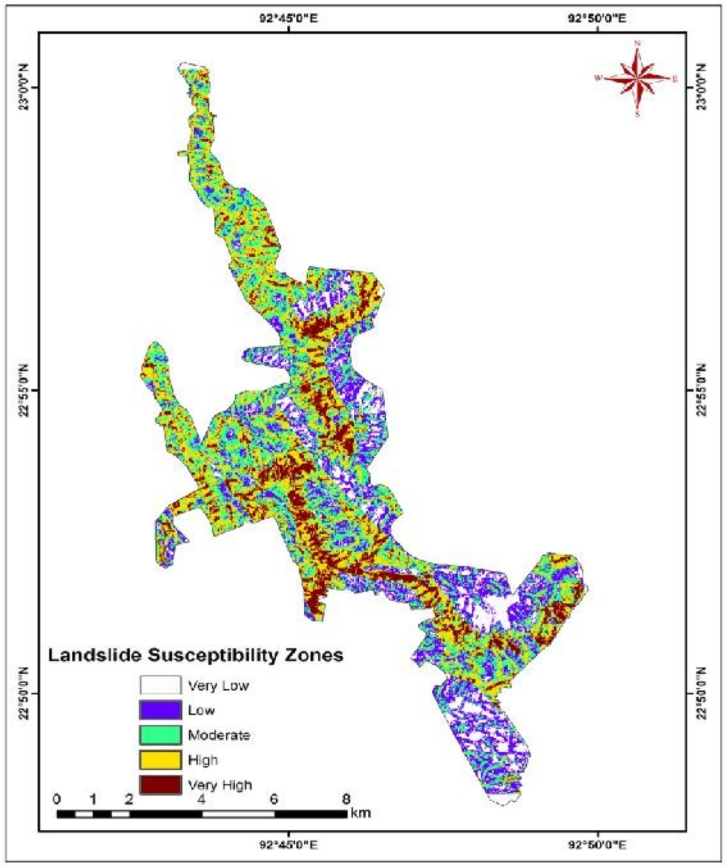

Fig.4.17: Landslide susceptibility map based on 114 (75%) landslides points

4.8 VALIDATION OF THE LANDSLIDE SUSCEPTIBILITY MAP

Since the Landslide susceptibility map (LSM) generated shown in Fig 4.17 above is based only on 75% of the total landslides recorded in the study area, it should be validated to prove that the map is useful and reliable. The validation is done whether the predictions of susceptible zones matches the expected results. For validation of the LSM, the reclassified map was converted into vector layer and 25% of the landslides not used for calculating the frequency ratio were used. Intersect analysis was carried out again to find out how many of these landslides (ie.38 landslides or 25%) falls in the landslide susceptibility zones. From the result of the analysis, it shows that 30 landslides out of 38 landslides ie.78.747% fallS in high and very high susceptible zones. This shows that the landslide susceptibility map is reliable.

Table. 4.10. Percentage of landslides, and frequency ratio of the 38 landslides

Sl. No	Landslide Susceptibility Classes	LS	LS%	Pixels domain	Pixel %	Frequency Ratio
1	Very Low	1	2.631579	7607	10.408	0.252842
2	Low	3	7.894737	15937	21.80522	0.362057
3	Moderate	4	10.52632	20655	28.26045	0.372475
4	High	14	36.84211	18934	25.90576	1.422159
5	Very High	16	42.10526	9955	13.62057	3.0913
Total of High & Very High		30	78.94737	28889	39.52632	4.513459

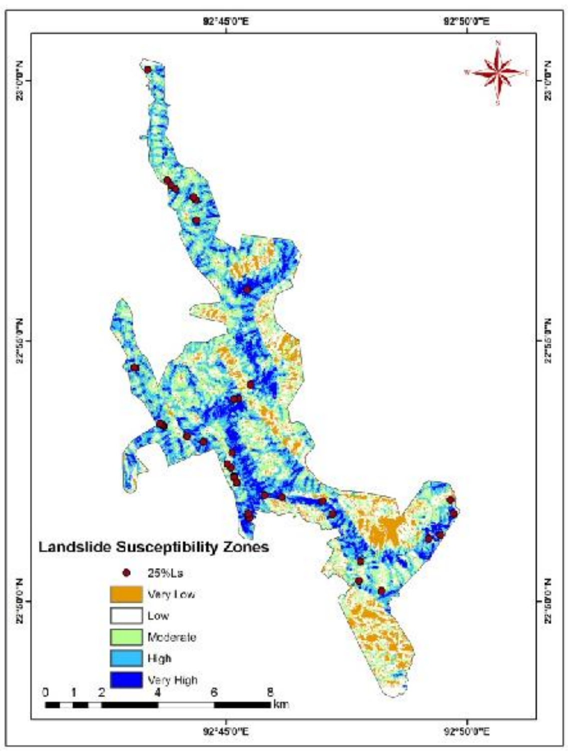

Fig.4.18: Landslide susceptibility map based on 38 (25%) landslides point

4.9. Influence of the causative factors in landslide susceptibility

For the preparation of Landslide Susceptibility map 7 causative factors were used. However the LSM may show differences if the input of the causative factors were change. A factor which causes landslide in a particular area may not induce landslides in another area. So, the influence of each causative factors in the LSM can be find out by repeating the overlay analysis by excluding one of the factors each. This method is known as verification and effect analysis by Lee and Talib (2005). According to them "Effect analysis studies show how a solution changes when the input factors are changed. If the selected factor results in a relatively large change in the outcome, then the outcomes is said to be effective to that factor. Effect analysis quantifies the uncertainty of each factor. The factors that have the greatest impact on the calculated landslide susceptibility map can therefore be identified using effect analysis". (Lee and Talib, 2005)

Table 4.11 (A) showing the influence of the different causative factors on LSM

LS Zone	All the causative factors		Excluding Slope		Excluding Drainage Density	
	No of Landslides	% of landslides	No of Landslides	% of landslides	No of Landslides	% of landslides
Very Low	2	1.754386	2	1.754386	1	0.877193
Low	7	6.140351	8	7.017544	10	8.77193
Moderate	20	17.54386	19	16.66667	19	16.66667
High	43	37.7193	45	39.47368	46	40.35088
Very High	42	36.84211	40	35.08772	38	33.33333
High & Very High	85	74.5614	85	81.57895	31	73.68421
Variation in High & Very High			0		-0.87719	

Table 4.11 (B) showing the influence of the different causative factors on LSM

LS Zone	Excluding Distance to Drainage		Excluding Landuse		Excluding Plan Curvature	
	No of Landslide	% of landslides	No of Landslide	% of landslides	No of Landslide	% of landslides
Very Low	3	2.631579	1	0.877193	1	0.877193
Low	6	5.263158	10	8.77193	6	5.263158
Moderate	26	22.80702	21	18.42105	16	14.03509
High	51	44.73684	37	32.45614	49	42.98246
Very High	28	24.5614	45	39.47368	42	36.84211
High & very high	79	69.298	82	71.929	91	79.842
Variation in High & Very High		-5.26316	-2.63158		5.263158	

Table 4.11 (C) showing the influence of the different causative factors on LSM

LS Zone	All the causative factors		Excluding Lithology		Excluding Structure	
	No of Landslides	% of landslides	No of Landslides	% of landslides	No of Landslides	% of Landslides
Very Low	2	1.754386	2	1.754386	1	0.877193
Low	7	6.140351	13	11.40351	11	9.649123
Moderate	20	17.54386	31	27.19298	19	16.66667
High	43	37.7193	40	35.08772	39	34.21053
Very High	42	36.84211	28	24.5614	44	38.59649
High & Very High	85	74.5614	68	59.64912	83	72.80702
Variation in High & Very High			-14.9123		-1.75439	

4.10. Final Landslide Susceptibility Map

After validation, the final Landslide susceptibility map was generated by repeating all the processes such as reclassification, intersect analysis and overlay analysis. The frequency ratio based on 152 landslides was calculated in order to generate the final Landslide susceptibility. The number of landslides that falls in each zone was calculated and 118 landslides fall in high and very high zones which is 77.63% of the total landslides recorded. The percentage of landslides falls in high and very high zones yield good result and majority of the area is covered in these zones.

Table. 4.12. Percentage of landslides, and frequency ratio of the 38 landslides

Sl. No	Landslide Susceptibility Classes	LS	LS%	Pixels domain	Pixel %	Frequency Ratio	Area in sq.km
1	Very Low	3	1.973	5743	7.879	0.250	6.37
2	Low	8	5.263	14519	19.919	0.264	13.1
3	Moderate	23	15.131	21673	29.734	0.508	19.5
4	High	61	40.131	20336	27.900	1.438	18.3
5	Very High	57	37.5	10617	14.566	2.574	9.55
Variation in High and Very High		118	77.63				

The variation in the frequency ratio between 75% and 100% landslides is shown in table 4.13. And it shows that majority of the frequency ratios shows minor variation.

Factor	Class	Frequency ratio based on 114 landslides (75%)	Frequency ratio based on 152 landslides (100%)	Variation
Slope	0-5	0.382	0.574	-0.191
	5-15m	0.794	0.793	0
	15-25	1.067	1.119	-0.053
	25-35	1.155	1.139	0.016
	>35	0.963	0.783	0.180
Drainage Density	Very Low	1.213	1.194	0.019
	Low	1.304	1.345	-0.04
	Moderate	1.006	0.955	0.050
	High	0.852	0.864	-0.012
	Very High	0.211	0.211	0
Distance to Drainage	0-50m	1.872	1.900	-0.028
	50-150m	1.118	1.071	0.047
	150-250m	0.793	0.832	-0.039
	250-300m	0.163	0.244	-0.081
	300-350m	0	0	0
	>350m	0	0	0
Landuse/Land Cover	Agriculture Plantation	1.039	0.779	0.259
	Jhum/ Cultivated Land	1.075	1.075	0
	Built Up/ Settlements	1.915	2.181	-0.266
	Scrubland	0.937	0.777	0.160
	Less dense forest	0.398	0.498	-0.099

Factor	Class	Frequency ratio based on 114 landslides(75%)	Frequency ratio based on 152 landslides(100%)	Variation
Landuse/ Land Cover	Open Forest	0.918	0.880	0.037
	Water body	0	0	0
Plan Curvature	-14.87 to 1.45	0.431	0.808	-0.377
	-1.45 to -0.41	1.011	1.027	-0.016
	-0.41 to 0.37	1.200	1.080	0.120
	0.37 to 1.33	0.892	0.980	-0.087
	1.33 to 20.31	0.527	0.527	0
Structure	Very Low	0.906	0.833	0.073
	Low	1.059	1.375	-0.315
	Moderate	1.051	1.013	0.037
	High	0.898	0.486	0.412
	Very High	1.279	1.744	-0.465
Lithology	Shale-sandstone	0.213	0.229	-0.015
	Shale-Siltstone	1.660	1.516	0.144
	Siltst-Shale	1.018	0.967	0.050
	Sandstone	1.337	1.522	-0.184
	Crumpled shale	0.606	1.364	-0.757
	Gravel,sand,silt&clay	1.275	0.956	0.318

Table 4.13. (a & b)Variation in Frequency ratios when 75% and 100% of the slides are used

The Landslide Susceptibility Map (LSM) prepared shows that area with very high landslide susceptibility forms a lesser extent and are mainly concentrated along the western, northwestern, southern part of the area and near Zobawk .High susceptibility zones are also mainly in the margin which is generally devoid of settlements and like College veng, Zotlang are located in the high susceptibility zones. Care should be undertaken when developmental activities are carried out in these place and steps should be taken to avoid any large scale housing expansion schemes.

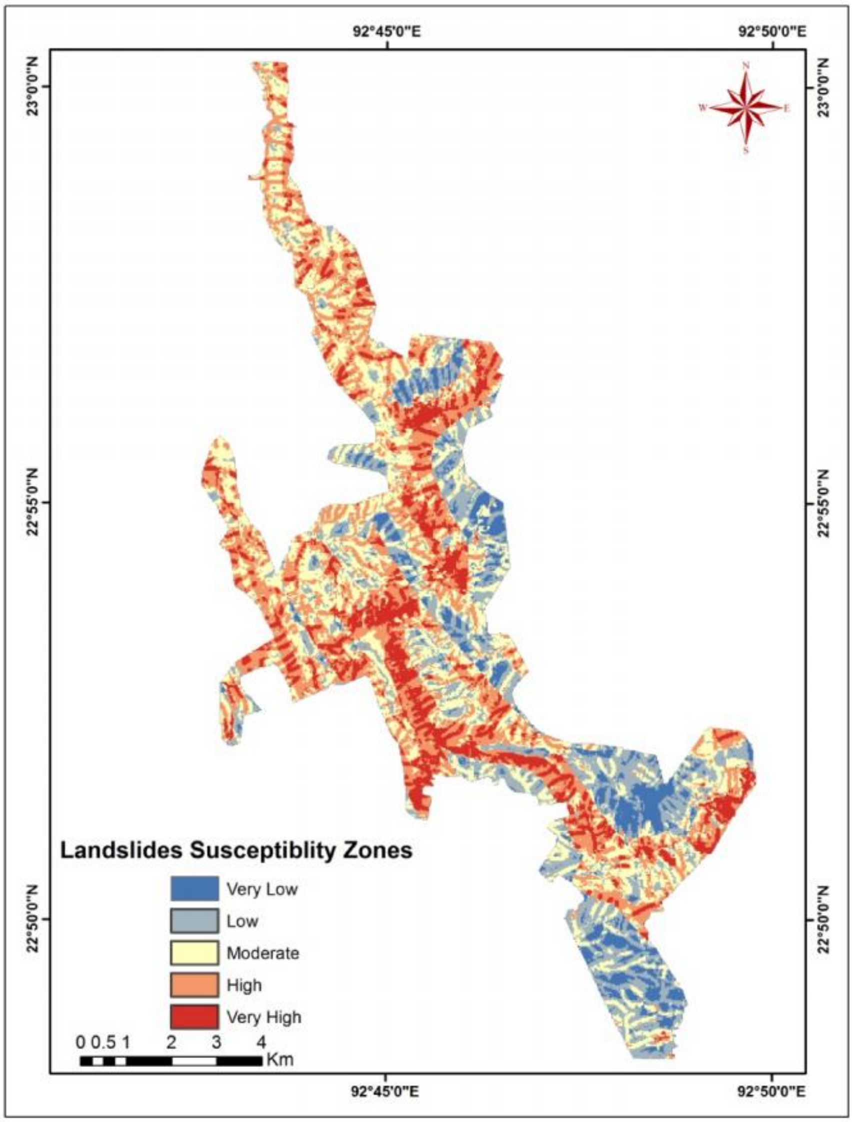

Fig.4.19: Landslide Susceptibility Map of the study area

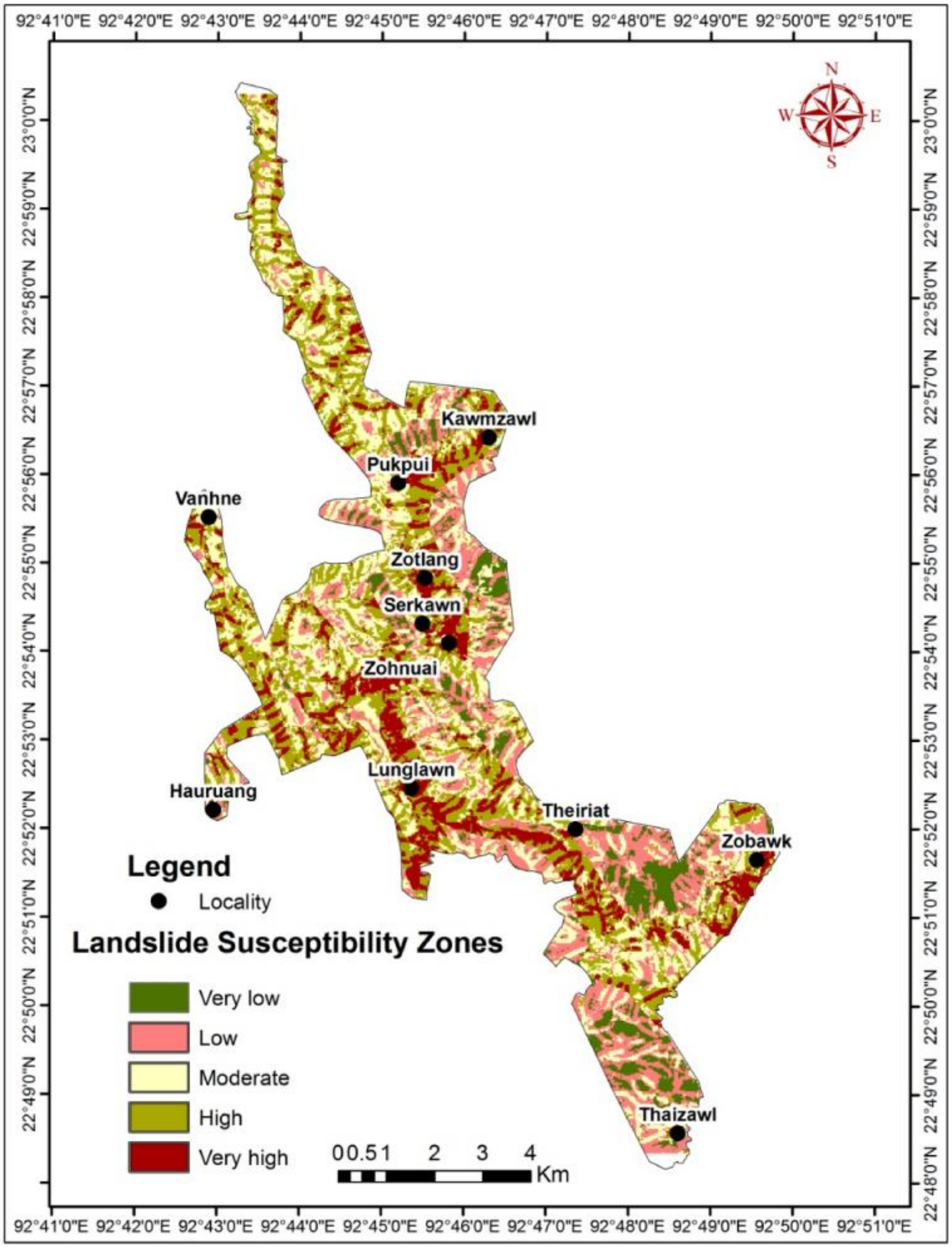

Fig.4.20: Locality plotted on the Landslide Susceptibility Map of the study area

5. SUMMARY AND CONCLUSION

5.1. SUMMARY

Landslides are one of the most common natural hazards in mountainous region. In North-east India, several slides have been reported and especially in Mizoram over 1000 slides have been reported during the past 30 years. Major events of landslides have occurred in 1893, 1929, 1965, 1983, 1992, 1995, 1996, 2013 to 2019 in the State. Though several landslides occur every year, some of these landslides are just minor slips. On th other hand, some landslides are disastrous and cause loss of life, damage to property and disruption of communication and transportation systems, and destruction of natural resources. The landslides that have occurred in recent years have taken place in areas close to settlements burying the houses with debris. 2018 and 2019 landslides that took place within the study area can be referred as a tragic events because many houses were shattered and even caused loss of lives. This indicates that people have established their homes in vulnerable areas without any restrictions or control. With increase in population and developmental activities it can be foreseen that urban development will be outstretch to areas susceptible to landslides. Hence, it is necessary to investigate/study the area to identify safe zones for urban development and identify the landslide prone areas so as to regulate and impliment measures for strengthening the slope in order to prevent future failure.

There are different methods for landslide susceptibility mapping which include heuristic, deterministic, and statistical approaches which have been reviewed comprehensively by Guzzetti *et al*. (1999) and Chacón *et al*. (2006). Heuristic approach is considered as a direct or semi-direct landslide hazard mapping method which relies on the opinion of the expert and subjective weightage assignment. Deterministic approach is substantially used to observe landslides which are reactivated and involves slope stability analysis. The statistical methods are more common and are based on calculation of slope failure susceptibility using bivariate or multivariate methods. In this method the combination of variables that are responsible for landslide in the past are assessed and the weightage is calculated for further overlay analysis. While heuristic approach depends on expert opinion and the weightage assigned by two experts is not the same, it is semi-quantitative. Deterministic approach are often used to monitor active slides and for larger areas, the tactic are often used as long as the terrain conditions are same throughout the area that is under investigation. Statistical methods are more quantitative and suitable for the study of Mizoram landslide and can be easily used with remotely sensed data and GIS techniques. Statistical method for Landslide susceptibility zonation is therefore used for investigating the landslides in and around Lunglei town. "Landslide Susceptibility Zonation by statistical methods is based on the assumption that past is the key to future and past landslide occurrences are controlled by landslide causative factors and future landslides will occur under the same conditions as past landslides". (Lee and Pradhan, 2006).

5.1.1. Selection of method

Over the last decade, the development in Geographic Information Systems (GIS) and landslide susceptibility assessment methods have given diverse facilities in applying landslide susceptibility mapping programs. Given a fixed of geoenvironmental situations, landslide susceptibility is the chance of spatial incidence of recognized slope failures (Guzzetti et al., 2005). It is assumed that landslides will occur inside the destiny due to the identical situations that produced them in the beyond (Guzzetti et al., 1999), susceptibility assessments can be used to expect the geographical location of future landslides (Chung and Fabbri, 1999; Guzzetti et al., 2005).

Several papers related to GIS application for landslide mapping and assessment have been published since 1990s. Varnes (1984) manuscript on landslide hazard Zonation initiated numerous landslide evaluation studies worldwide. The frequency ratio, weights of evidence and logistic regression are the most common methods followed for landslide susceptibility mapping. Some people have used more than one technique for the mapping and feature as compared to the predictive ability of various techniques. These researches suggest that frequency ratio and weights of evidence techniques are simple and give accurate outcomes. Hence, the frequency ratio method is used for the present study.

The landslide susceptibility map is based on the principle that the past and present are keys to the future. "To assess landslide susceptibility for an area, it is necessary to identify and remap both the conditioning factors and landslide locations. A remap table defines how the values will be reclassified in the new spatial database that is supported by integer values". (Silalahi, *et al.*, 2019). Two bivariate probabilistic techniques were used and are primarily based on 75% of landslides from the landslide inventory map and 7, causative factors. The map become validated via overlying the unused landslide points. The percent of landslides falling in different zones show majority of the unused landslides. (>80%) of the landslides fall in regions with higher landslide susceptibility. The causative factors recognized are slope, land use, drainage density, distance to drainage, plan curvature, structure and lithology. The various layers had been categorized for overlay analysis.

Slope even though is the primary cause of landslides decreases the validation as the frequency ratios do not show progressive variation and regions with high and very high slopes have lesser chance of landslides with values 1. Based at the influencing causative factors it's clear that type of soil, the geomorphic setup and drainage density which alters the percolation of rainwater in addition to the human activity like weakening of slope by toe cutting, and improper drainage system are the principle reasons of the slope instability.

5.1.2. Statistical Analysis by Frequency Ratio method and Validation

The frequency ratio method is widely used for landslide susceptibility mapping (Lee, and Sambath, 2006; Mezughi, et al., 2011; Lee, and Talib, 2005). The frequency ratio was calculated for Lunglei town and its vicinity. The percentage of landslides in each class and the extent of the class in the overall watershed were calculated and the percentage of landslide divided by using the share of the class gives the frequency ratio. The frequency ratio was assigned to the raster layers of 30 x 30 m pixel size and the landslide susceptibility index grows to be calculated via the summation of the frequency ratios of each pixel of the dissimilar layers. The Landslide susceptibility map is prepared using the LSI and was categorized into five zones of very low, low, moderate, high and very high landslide susceptibility

5.1.2. Validation of LSM

The motive of making preparing a LSM is to become identify of regions so that it will be affected by future events. The map prepared for Lunglei was validated by overlaying the remaining 25% landslides (38 landslide points) and as majority of the landslides fall in zones of the high and very high landslide susceptibility classes, the results are satisfactory. Indicating that the predictability of the map is good. Having validated the method, the final Landslide Susceptibility Map for Lunglei town and its vicinity was prepared by recalculating the frequency ratios and following the technique followed earlier. The overlay analysis of the landslides on the LSM organized based on FR calculated the usage of all the slides show the landslides falling in very high and high Landslide Susceptibility class 81.82%. Hence, the maps organized will truly identify the landslide prone zones and may be used effectively for town and land use planning.

5.2. Conclusion

- In this study, Frequency Ratio method was carried out and Lunglei town and its vicinity is taken up for the study area which covers about 66.82 km^2.
- In the Frequency Ratio Method, 7 causative factors namely slope, , drainage density, distance to drainage, landuse, plan curvature, structure and lithology were prepared with number of sub variables within each of the 7 landslide parameters. All these factors contribute to the results however the degree of influence are very contrasting. Parameters like landuse and lithology have greater impact as compared to other factors. Since all the causative factors have a positive influence on the landslides, they were all included for the final map preparation .

- Landslide susceptibility maps have been constructed using the relationship between each landslide and causative factors.
- The thematic map prepared for each causative factors were classified and reclassified again from the Spatial Analyst extension, if these layers are not in vector format they are again converted into vector for intersect analysis.
- 75% of the landslides were overlaid and intersect analysis is carried out in order to find out the frequency ratio for each causative factors.
- Layers were prepared for overlay analysis by reclassifying the different factors by assigning the frequency ratio prepared.
- In order to find out the landslide susceptibility index, weighted sum overlay analysis was carried out by adding all the causative factors by weighted sum tools present in Arc toolbox, this was again classified, reclassified and overlay analysis was again carried out using 25% of the landslide.
- Among the different causative factors slope plays a very important role, Landslide is maximum in an area where slope angle ranges from 15 to 25°to 25°-35°. But number of landslides occurrence decreases above 35°. This means that as the slope angle increases, then the shear stress in the soil or other unconsolidated material generally increase, though the landslide probability increases according to slope angle, it is not always the steep slope that are vulnerable to landslide. It can be said that undisturbed steep slope can also be more stable as compared to low angle slope which are frequently disturbed.
- Landuse pattern is also one of the most important factor in this study as Landslide are more frequent in builtup areas (27%) , cultivated land (18%) and open forest where cutting down of trees were common (43%)
- Landslide Susceptibility map was prepared by classifying the layers into five classes of landslide susceptibility zones namely very low, low, moderate, high

and very high. Then on these five classes, landslides were plotted and the landslides per unit area were worked out for each sub variable of the 7 class and landslide per sq.km was calculated.

- Very High susceptibility zone : Landslide is frequent in this zone, especially during and after rainfall. Most of the settlement area falls under this zone. College Veng, part of Zohnuai and Serkawn area, Zotlang (below Tourist Lodge) It is also found in part of Zobawk and lunglawn etc. Some part of Theiriat locality also falls within the very high susceptibility Zone. The quarry located within the study area falls in this zone. It can be said that Building settlements over the slope play an important role in the landslide occurrences in the study area, which can be observed from the high frequency ratio for the settlement class in the land use and land cover layers, the very high susceptibility zones mostly fall in areas where anthropogenic activities are frequent. This zone constitutes an area of 9.55 sq. km and forms 14.29 % of the total study area.

- The High susceptibility zone occupies an area of 18.3 km^2 which is 27.38% of the total study area while moderate susceptibility zone covers an area of 19.5 km^2. and occupies 29.18 % of the total study area. The low and very low susceptibility zones cover 13.1km^2. and 6.37 km^2. respectively.

- Majority of the landslides have occurred close to I and II order streams Since I^{st} and II^{nd} order streams usually constitute the upper part of streams they are in close proximity with human activities. Increase in the volume and velocity of stream discharge due to domestic and industrial waste combined with slope modification and may amplify the rate of erosion in the form of toe erosion etc leading to landslide activities

- The study area is under the direct influence of south west monsoon, with average annual rainfall of 2489.6 mm. From the data collected, it can be said that most of landslides occurs during the rainy season i.e. during the month of June to September. Maximum number of landslides were recorded during this period. Large amount of runoff due to prolonged rain and cloud burst etc increases the velocity and discharge of streams which increases the rate of erosion particularly toe erosion in I and ii order streams. Over saturation due to rainfall decreases the binding capacity of soil which decreases their stability especially in high angle slopes. Oversaturation can also increase the load leading to downslope movement of debris due to gravity. Rainfall increases the moisture content of rocks and as percent sorbtion of rock increases its strength decrease. It also increases percolation and reduces friction as they seep through bedding plnes, joint, fractures etc. This shows that rainfall is also an important triggering factors for the occurence of landslides in the study area.

- The landslide Susceptibility map prepared is validated and 78.947% of the slides have taken place in High and Very High susceptibility classes.
- The research findings will be helpful to the community and disaster management authorities in mitigation of the hazard.
- The final Landslide susceptibility map generated thus shows that the area under habitation and close to settlements are more prone to the occurrence of landslides. This suggests that the area under studies needs a strict directive or regulation to control slope modification in order to avoid massive landslides. Proper town planning is needed so that constructions and other developmental activities will not take place in areas vulnerable to landslides.
- For mitigation of Landslide in the study area proper awareness is needed on the alteration of natural landforms for the purpose of buildings, road constructions and other developmental activities. The general public have to be educated on the importance of geologist and geological reports prior to any projects involving excavation of land.

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