LANDSLIDE SUSCEPTIBILITY, VULNERABILITY AND RISK ASSESSMENT OF NOKLAK TOWN, NAGALAND

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in

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BY

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The thesis presented by Miss Mademshila Jamir bearing Registration No. PhD/GEL/00091 embodies the results of investigations carried out by her under my supervision and guidance.

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PREFACE

Worldwide, landslides incur catastrophic and substantial economic, human and environmental losses. A landslide is a geological phenomenon that includes a wide range of ground movements, such as rock-falls, deep failure of slopes and shallow debris flows. Landslides of different types are frequent in geodynamically active domains in the Himalayan and Indo-Myanmar ranges. Besides the complex geomorphic setting, the increasing rate of population and the expansion of settlements make it more vulnerable to landslide phenomena in these regions.

Noklak town, located in the easternmost part of India, lies near the tectonic contact between the Indian Plate and the Burma microplate, which makes the region tectonically active. Geologically, it is a part of the Inner Fold Belt, one of the major tectono-stratigraphic subdivisions of Nagaland, which consists dominantly of shales with minor intercalations of siltstones and sandstones of the Disang Group of rocks. Landslides have caused havoc to Noklak town and its citizens for more than four decades since 1980, affecting nearly one-fourth of the township and endangering the population and their assets. The slopes of the study area, which is part of a very hilly terrain, are highly unstable. In such a terrain, natural hazards like landslides are the most common and disastrous. This study therefore, aims at identifying and delineating the township into different zones based on their susceptibility, vulnerability and risk to landslides. The recent upgradation of Noklak town as the district headquarters has noticeably ushered in developmental activities. This has necessitated the formulation of different strategies to minimize and mitigate hazards, particularly due to landslides and considering the rapid developmental activities that will ensue with the recent upgradation of the subdivision to that of a district, the data generated will be useful for urban sprawl and land use planning, to minimize and mitigate the loss to life and property due to landslides. Therefore, the study area includes some portions beyond the present built-up area, so the Landslide Susceptibility Map and the Landslide Risk map generated from this study may be used as a tool of reference for any future developmental plans or expansion of the township, thereby suggesting recommendations that will be of immense help to planners, designers, engineers, etc., for necessary preparatory and mitigation measures during the development of this nascent town.

The thesis has been divided into six chapters. **Chapter 1** consists of the introduction of thesis which gives a general idea on landslides, their causes and socio-economic impacts. This chapter provides the statement of the problem and motivation for the study, information on the study area, its physiography and a detailed regional geological set up followed by objectives of the study. **Chapter 2** gives an account on the literature review of landslides, it's definition, classification and causative factors. This chapter gives an insight to the lists of works carried out by several authors on land instabilities of Nagaland and elaborates the different approaches for the preparation of Landslide Susceptibility map. It also gives a brief account on the scarcity of literatures for Vulnerability assessment and discusses Risk evaluation as the whole gamut of all exercises in landslide studies. **Chapter 3** gives a detailed account of the materials and methods used in the study, data collection and analysis involving a systematic and scientific approach for the preparation of a Landslide Susceptibility, Vulnerability and Risk map. The LSM was prepared with three Quantitative Bivariate Statistical methods, viz. Yule coefficient (Yc) method, Information Value method (InV), and Weight of Evidence method (WoE). The accuracy of the Landslide Susceptibility Map (LSM) was evaluated using the Success Rate Curve (SRC). The three LSMs prepared by employing the different methodologies are then validated using the Area Under Curve analysis and the map with the highest accuracy is then used for the preparation of Landslide Vulnerability and Risk map. With the data on degree of damage for each element at risk from the landslide hazard and LSM, using the vulnerability scale, the Vulnerability map is prepared. Risk assessment is then carried out using the Vulnerability map and LSM. **Chapter 4** provides the results of the study. **Chapter 5** discusses the significant landslide-causing factors in the area and draws the conclusion from previous chapters. **Chapter 6** suggests recommendations for the study area based on the scientific data generated, which delineate the area according to slope stability.

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CONTENTS

CHAPTER 1

INTRODUCTION

A landslide is a geological phenomenon and can be defined as the downward and outward movements of slope-forming materials along surfaces of separation due to gravity and other factors (Varnes, 1978; Cruden, 1991; Dikau et al., 1996). It is a type of mass wasting that is classified based on types of slope movements such as falls, creep, spread, topples, flows, and other complex movements and by the type of material involved, viz. bedrock, debris, or earth (Varnes, 1978; Crozier, 1986; Cruden and Varnes, 1996).

Warming of the earth's climate system is unequivocal, and such changes in climate affect the stability of natural and engineered slopes, which has consequences such as landslides (Gariano and Guzzetti, 2016). In India, landslides are mostly activated by monsoonal precipitation though it is also undeniable that humans are responsible for this global climate change (Wadhawan, 2019). Besides global warming, several anthropogenic activities have caused an increase in landslide incidences all over the world (Kaushik and Nirmala, 2021). Deforestation, road construction, undercutting of slopes in steep mountainous areas, development of settlement areas (Bruschi et al., 2013), and other changes in land use and land cover (Galve et al., 2015; Meneses et al., 2019). Landslides are also the result of the complex spatio-temporal interaction of numerous environmental factors (Pisano et al., 2017), such as lithology, structure, seismicity, hydrology, and topography (Guzzetti et al., 2006a; Nandi and Shakoor, 2009; Pourghasemi and Rossi, 2017).

Landslides are considered the 3rd most fatal disaster globally, and it accounts for approximately $400 billion in loss annually and poses a major risk to buildings, roads, infrastructure, and people (Pinyol et al., 2012; Abancó & Hurlimann, 2014). They cause serious catastrophes, including injuries, human casualties, and immense environmental and economic losses every year (García-Ruiz et al., 2010). India is regularly affected by landslides, and Wadhawan (2019) identifies the hill slopes of the Himalayan and sub-Himalayan landscapes of Northeast India, the Western Ghats, and the Nilgiris in Tamil Nadu and Konkan ranges as susceptible to landslides. As per NSDMA (2022) website, more than 12% of the Indian territory is prone to landslides and is responsible for the loss of nearly 300 people each year. Nagaland being a dominantly hilly state, has also seen an increase in the incidences of landslides, especially in the last few decades.

Nagaland is situated in the extreme northeast corner of the Indian subcontinent bordering Myanmar, between 25°11'12.09" and 27°02'8.74"N latitudes and 93°19'22.40" and 95°15'22.95"E longitudes occupying an area of 16,579 sq km. The state consists predominantly of high hill ranges with some low-lying regions along the western margin bordering Assam and represents a tectonically complicated, relatively young, immature, mountainous terrain. It is part of a highly dissected major mobile belt of the westernmost morphotectonic unit of the Burmese Orogen. This belt, believed to be still rising, continues north into the eastern Syntaxial Bend of the Himalayas. To the east lie the central lowlands of Myanmar, and on the west are the Mikir Hills Precambrian massifs and Brahmaputra trough. The eastern margin represents part of the subducting Indian Plate beneath the Burma microplate. Intense and continuing tectonism is responsible for extensive folding, jointing, fracturing, shearing, and faulting of the rocks in this geodynamically sensitive region. The high amount of rainfall and other geomorphic processes have also further weakened the rocks through weathering and erosion, causing large-scale surface instabilities, particularly during the monsoon.

Landslides are the most common geohazard in Nagaland. Besides rugged terrain, complex geomorphic and tectonic settings, climatic factors, etc., human activities due to rampant and unscientific developmental activities have led to further instability in this part of India (Lotha, 1994; Bhattacharjee et al., 1998; CRRI, 2000; Hiese, 2004; Aier, 2005; Walling et al., 2005, 2016, 2021; Thong et al., 2006, 2009, 2011; Singh et al., 2008; Aier et al., 2009, 2012; Jamir et al., 2011; Sothu et al., 2011; Jamir, 2013; Supongtemjen & Thong, 2014, 2021; Supongtemjen et al., 2015; Jamir et al., 2019, 2022; Chang et al., 2021; Khalo et al., 2016).

1.1. Statement of the problem and motivation

Noklak town has suffered immensely from the scourge of landslides. However, due to its remoteness and problems with connectivity, it eluded the attention of the scientific community for several decades. Due to such neglect, very little published data is available about the geology and also on the socio-economic implications of the landslides. Several landslide interventions have been attempted by different agencies in the past, yet no detailed geological investigations have been carried out so far. The recent upgradation of Noklak town as the district headquarters has noticeably ushered in developmental activities. This has necessitated the formulation of different strategies to minimize and mitigate hazards, particularly due to landslides. Towards this end, a systematic and scientific approach involves the preparation of a Landslide Susceptibility and Risk map. The present study will therefore generate scientific data to delineate the area according to slope stability and suggests recommendations that will be of immense help to planners, designers, engineers, etc., for necessary preparatory and mitigation measures during the development of this nascent town.

1.2 Study area

The present built-up area of Noklak town and its surrounding, with a total area of 4.24 km^2, has been taken up for the study. Noklak town is the administrative headquarter of the newly established Noklak district (20th January 2021), formerly part of Tuensang district. The study area lies at an average elevation of ~1480 m above mean sea level and is one of the easternmost townships of India bordering Myanmar. It is situated ~350 km away from Kohima town, the state capital of Nagaland (Fig. 1.1).

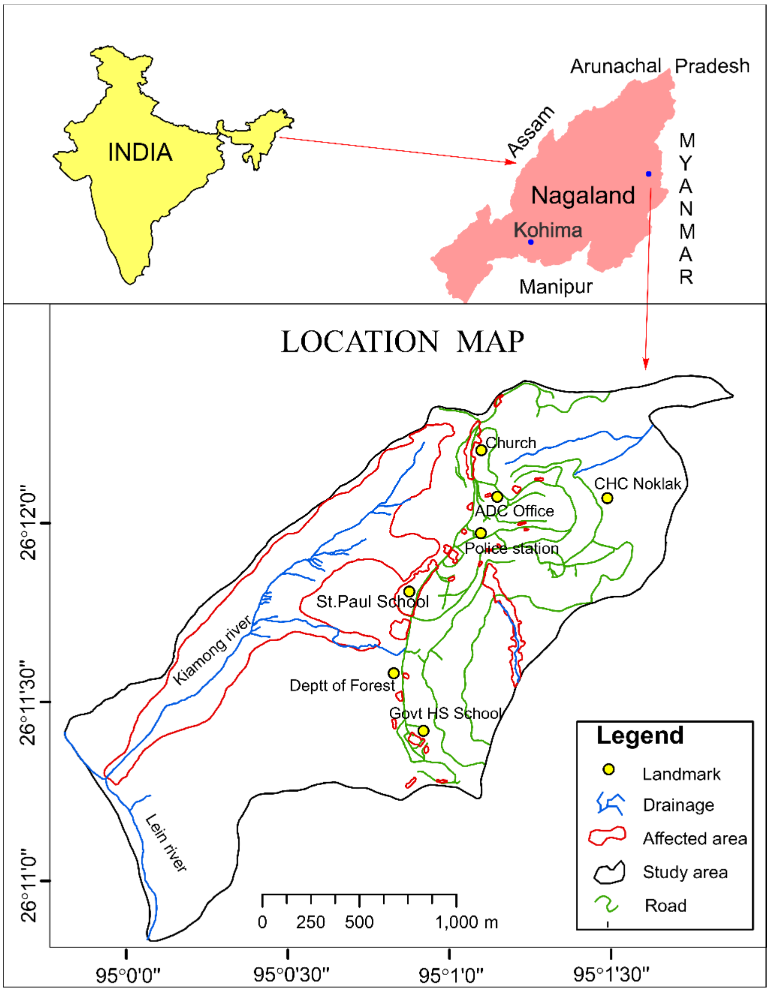

Fig. 1.1. Location map showing the study area

The study area is part of the Survey of India topographic sheet no. 83 N/4, and it lies between 94°59'48" & 95°01'54" E longitudes and 26°10'54" & 26°12'24" N latitudes. There are no previous records, and interviews conducted during the course of the study suggest that the town enjoyed a fairly stable slope condition prior to the 1980s. The residents recall the occurrence of a minor landslide that affected the western part of the township in 1980. This has become a major unstable zone during the last four decades, affecting a total area of 0.82 km^2. (Fig 1.2). Moreover, several incidences of land instabilities have occurred in different parts of the town in recent years, affecting a number of roads (Fig 1.3), buildings (Fig 1.4), forest cover, and cultivated tracts, including the only road connecting the International Trade Centre of India and Myanmar, at Pangsha (Dan). The sewage and drainage setup of the town is relatively nil.

Fig 1.2. Part of Noklak town seen on the ridge top. (a,b) Part of the township affected by a major landslide and continuing subsidence; a small portion of the old landslide zone of the 1980's is now covered by vegetation

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Fig 1.4. (a) Tension cracks developed inside of Government Guest House due to subsidence (b) Classrooms and office of the St. Paul School and part of the school compound affected by ground subsidence (c) Tension cracks developed inside of a residential building due to subsidence (d) House damaged due to subsidence

1.2.1. Geomorphology and Drainage

The area is marked by rugged topography consisting of moderately dissected structural hills with steep slopes and narrow valleys with high drainage incisions. Gullies and rills are common in the area.

The main drainage in the study area is the SSE-flowing Lein River. The SW-flowing Kiamong River is a tributary of the Lein River, where almost all the surface runoff from the northern portion of the study area is channelized (Fig 1.1). The other minor streams in the area are Punyao nullah and Pengan nullah.

1.2.2. Climate and rainfall

The climate falls in the sub-tropical and sub-temperate regions, where summers are pleasantly warm, and winters are cold. The average temperature falls to about 5°Celsius in January, which is the coldest month of the year, and rises to about 28°C in summer during the hottest month, usually in July. Heavy rainfall and storms are common specially during the monsoon season (May to September), with an annual average of 1200 mm (Source: Directorate of Soil & Water Conservation, Nagaland).

1.2.3. Population and livelihood

Noklak district is inhabited predominantly by the Khiamniungan Naga tribe and is popular for its cane work and handicrafts. Noklak town has a population of 7674 with 1384 households (Census of India, 2011). Agriculture is the mainstay of the local population. People cultivate irrigated terrace fields and also practice jhum (slash & burn) cultivation, where they grow maize, rice, Job’s tears, fox-tail millet, kidney beans, colocasia, etc. They also rear livestock such as cattles, crossbreed pigs, mithuns local poultry, goats, etc.

1.2.4. Geological setting

Nagaland is subdivided into four major tectonostratigraphic divisions (Ghose et al., 1987), which, from east to west, are– the Metamorphic Complex, Naga Hills Ophiolite (NHO), Inner Fold Belt, and the Belt of Schuppen. Noklak town lies within the Inner Fold Belt region, with the NHO to its east. Lithologically, the study area is made up of the Disang Group of rocks of the Upper Cretaceous - Eocene age and the Barail Group of rocks belonging Oligocene age. The Disang are represented by thick beds of splintery shale with intercalations of sandstone, while the Barail is made up of massive sandstone with intercalations of thin papery shale. The subduction of the Indian Plate beneath the

Eurasian Plate (Burma microplate) have caused a NW-SE compression, with the major lineaments of Nagaland trending approximately NE-SW. All compressional structures, such as folds and reverse faults, are parallel to the regional NE-SW trend. Tensile fractures and normal faults have developed parallel to the NW-SE compression direction. The stratigraphy of the study area is shown in Table 1.

Table 1: Stratigraphy of the study area (modified after Mathur and Evans, 1964; DGM, 1978; Ghose et al., 2010)

Age	**Group**	**Formation**	**Palaeogene Inner Fold Belt**
Oligocene	Barail	Renji	Hard ferruginous and thickly bedded sandstones
		Jenam	Alternating sandstone, siltstone and grey to dark grey shale with some coal seams
		Laisong	Medium to fine grained, well bedded, hard, grey laminated sandstone alternating with grey shale, sandy shale and siltstone
Upper Cretaceous to Eocene	Disang	Upper	Grey, khaki grey, black splintery shales with silty interbands, lensoidal sandstones and rhythmites
		Lower	

Disang Group

The Disang Group of rocks is the most common rock in the Inner Fold Belt of Nagaland. It is predominantly represented by thick monotonous sequences of splintery shale, that is grey, khaki grey, or black in colour, with intercalations of siltstones and fine-grained sandstones (Mallet, 1876; Mathur and Evans, 1964). This group comprises flysch sediments (Directorate of Geology and Mining, Nagaland 1978). The Disang Group is further subdivided into two distinct formations, a basal argillaceous and an upper arenaceous horizon designated as Lower and Upper Disang formations respectively (Sinha et al., 1982). The Disang shales are prone to spheroidal weathering and the development of concretions. The formation is shaly towards the basal part, while coarse-grained layers are more abundant higher up. Shale pellets are seen parallel to the bedding (Devdas and Gandhi, 1985; Sarma, 1985). The contact of sandstone with shale can be very sharp; the former stands out prominently as bands within the weathered shales.

Barail Group

The rocks of the Barail Group conformably lie above the Disang Group. This group consists of sandstones intercalated with thin beds of siltstone and shale, representing flysch facies (Brunnschweiler, 1966). This group is further subdivided into three formations, the oldest Laisong, overlain by the Jenam, followed by the youngest Renji Formation (Mathur and Evans, 1964).

The rocks in the study area are predominantly made up of shale of the Disang Group. The shales are dark grey to fawn-colored, splintered and sheared, and weathered to various degrees that have possibly been affected by minor metamorphism. The rocks exhibit 3-4 sets of joints and are highly fractured (Fig 1.5). Exposures of numerous quartz veins and slickenside (Fig 1.6) point to extensive tectonic disturbances in the area. The soil cover in the study area ranges from 3-5 m in thickness.

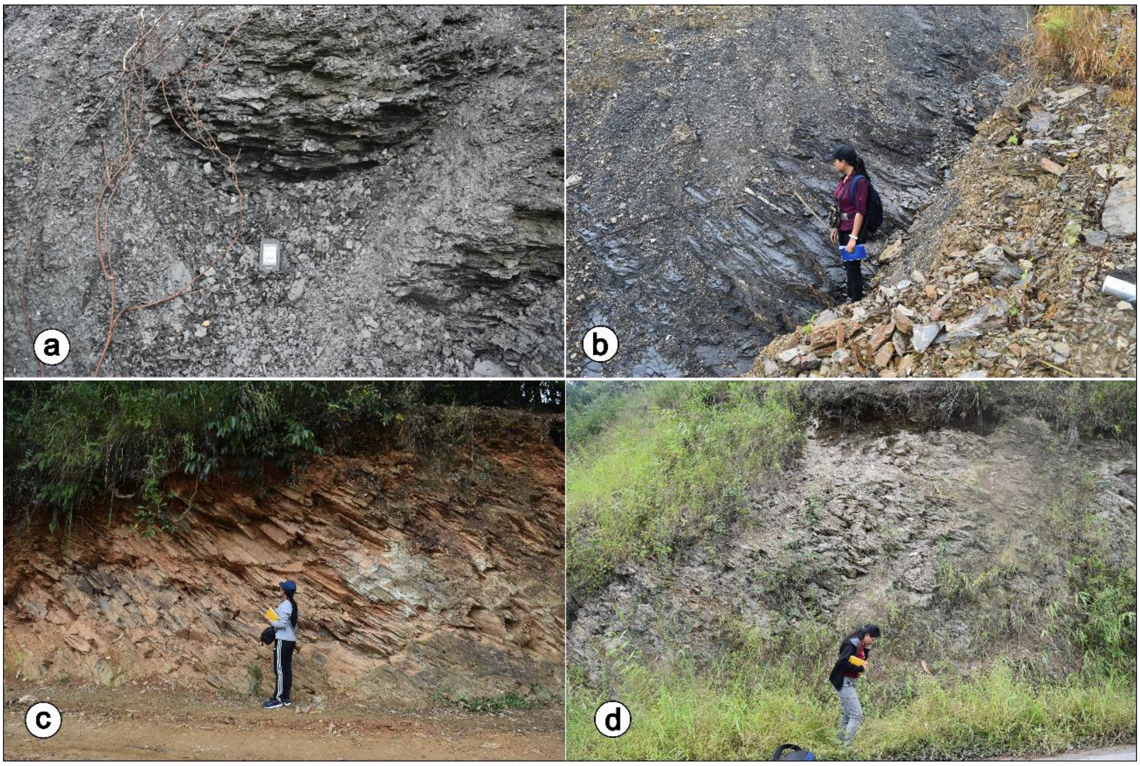


Fig 1.5. **(**a) Splintery shale (b) Weathered and crumbled shale exposure (c) Well bedded and jointed shale exposure (d) Fractured shale

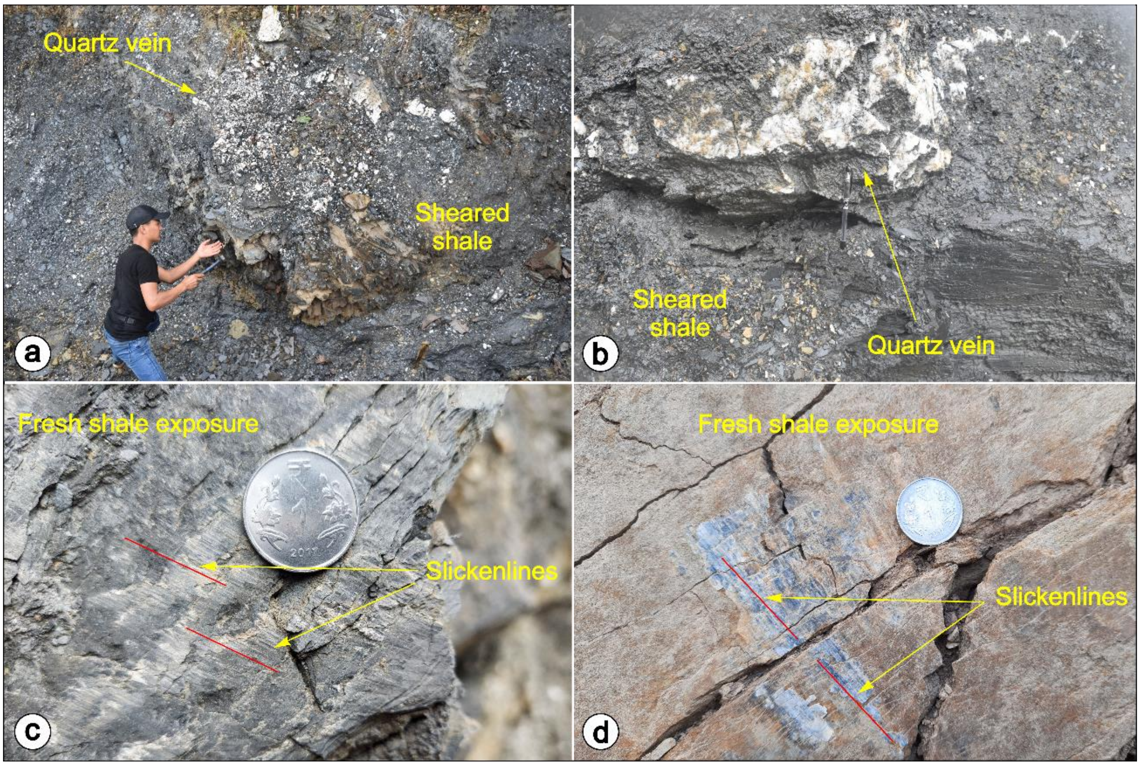


Fig 1.6. (a,b) Quartz veins in highly sheared and partially weathered shale (c,d) Slickenside in fresh fractured shale exposure

1.3 Objectives

The recent upgradation of Noklak town as the district headquarters has noticeably ushered in extensive developmental activities. It is also essential to understand the slope conditions in the area as regard to stability, keeping in view the eminent urban sprawl in the near future. In this backdrop, the following objectives were chosen for the study:

a) To prepare a Landslide Susceptibility Map.

b) To evaluate the vulnerability and risk assessment due to landslides.

c) To provide suitable recommendations.

CHAPTER 2

LITERATURE REVIEW

The earth's landscape is constantly in a state of dynamic change due to different geomorphological processes including erosion and mass wasting. Landslides are one such change that occurs frequently specially in mountainous terrains, that can potentially affect the general quality of life (Sharma et al., 1996; Karsli et al., 2009; Ray and De, 2009; Pathak, 2016). Landslide is considered the most fatal natural hazard, threatening socioeconomic conditions by damaging properties and vital infrastructure every year and also takes a huge toll on human lives at a global level (McKean,1991; Pradhan, 2010; Crozier and Glade, 2005; Tofani et al., 2013). The worst affected areas are in developing countries where 95% of landslide incidences occur, causing an annual loss of 0.5% of the gross national product (Chung et. al, 1995). Incidences of landslides are very common in India. According to a study conducted by the Geological Survey of India, the nodal agency for landslide management of the country, approximately 0.49 million km^2 (15 % of the land area) is vulnerable to landslide hazards, of which, 0.098 million km^2 is distributed in the north-eastern region of India (www.gsi.gov.in, retrieved on September 2022).

Landslides occur when the forces acting down-slope exceed the shearing strength of the materials that make up the slope, and although gravity is the primary driving force, other contributing factors also affect slope stability (Werner and Friedman, 2010). They are controlled by physiographical, topographical, lithology, meteorological, vegetation, and other parameters (Sharpe, 1938; Reed, 1992; Jamir et al., 2017, 2019; Tohari, 2018). The influencing factors may include water seepage, surface erosion by flowing water, geological structures, sudden lowering of the water table adjacent to a slope, earthquakes, and geotechnical properties of rocks and soils (Murthy, 2001). Weathering of rocks, soil erosion, tectonism, and anthropogenic interventions viz. deforestation, agricultural practices, slope cutting for roads or buildings, etc. also weaken slope stability and make them vulnerable to failure.

Although it is viable to carry out landslide studies with in-situ observation, it is tedious, cost-ineffective, and at times challenging for data collection in inaccessible terrains. The application of remote sensing and geospatial technology in landslide studies in recent times, however, has made it very convenient and feasible for researchers to study and monitor landslides to a great extent due to its extensive area coverage and frequency of observations, especially in inaccessible high mountainous areas (Mantovani et al., 1996; Kääb, 2000; Metternicht et al., 2005; Cheng et al., 2013).

2.1 Classification of landslides

Various landslide classification schemes have been proposed by several workers (Campbell, 1951; Zaruba and Mencl, 1969; Crozier, 1973; Hutchinson, 1978; Coch, 1995; Smith, 1996). However, Varnes's (1978) classification is most widely used based on two important parameters viz. the type of movement and materials involved (Table 2). Recognition of the type of landslides is a prerequisite in any scientific landslide investigation, as this will deliver a lot of information regarding the type of movement, rate of movement of materials, etc. This makes it easier to study land instabilities as it reduces the multitudinous details of related phenomena to a few easily recognized elements on the basis of common attributes (Crozier, 1984; Msilimba, 2002).

Table 2: Classification of landslides (Varnes, 1978)

Type of movement		**Type of material**		
		Bedrock	Debris (*coarse*)	Soil (*fine*)
Falls		Rock fall	Debris fall	Earth fall
Topples		Rock topple	Debris topple	Earth topple
Slides	Rotational		Debris slump	Earth slump
	Translational	Rock block slide Rock slide	Debris block slide Debris slide	Earth block slide Earth slide
Spreads		Rock spread	Debris spread	Earth spread
Flows		Rock flow	Debris flow	Earth flow
Complex movements		Combination of two or more principal types		

Topples

Topples are the result of outward and forward rotation of blocks of rocks, which usually occurs along steep surfaces such as cliffs, devoid of vegetal cover and penetrated by joint planes, fractures, and bedding. According to Hoek and Bray (1977), toppling failure can occur in slopes cut in rock with regularly spaced fractures, which strike parallel to the slope and dip into the face. The main relative factor is the action of gravity influenced by the weight of the falling blocks usually due to basal erosion or instability.

Falls

A Fall involves the sudden collapse or fall of rocks or debris along very steep slopes and is strongly influenced by gravity. This type of movement occurs either by falling through the air, bouncing, or rolling and for a short time may lose contact with the underlying rock or slope (Nemcok et al., 1972; Crozier, 1984; Bryant, 1991; Alexander, 1993). They may be also influenced by pore water pressure along joints and fractures and mechanical weathering, which weakens and breaks down the slope material. The fallen materials accumulate at the base of the cliff.

Slides

Sliding is the gradual down-slope movement of rock or soil along one or more well-defined slip surfaces that are characterized by almost permanent contact between the moving mass and the slide surface (Nemcok et al., 1972; Crozier, 1984; Bryant, 1991; Alexander, 1993; Smith, 1996). Sliding failure occurs when the geological structure dips out of the face (Hoek and Bray, 1977). Depending on the slip surface of contact, two types of slide movements are identified viz. translational and rotational slides. Rotational slides show a curved slip surface and are usually very deep and produce slumps by backward slippage, whereas translational slides are relatively flat, denoting planar movements, and are comparatively shallower. They generally have pre-existing slide planes that are activated during the slide event (Alexander, 1993; Smith, 1996).

Flows

Down-slope movement of materials as fluids is classified as Flows. The fluidity of the material is due to large quantities of water, such that the slope material becomes oversaturated and starts flowing in a semi-liquid state. They are slope movements in rocks and soils, analogous to the movements in liquids, and are classified as solifluction, mudflows, earth flows, rock streams, and debris avalanches (Nemcok et al., 1972; Varnes, 1978; Coch, 1995). The most common type is the debris flow (Corominas et al., 1996) which is regarded as the most dangerous (Takahashi, 1991) as they often extend far from their sources and their depositional areas can often include inhabited sites.

Creep

According to Varnes (1978), Creep is a deformational movement that continues under constant stress. It is one of the least destructive mass movement phenomena, which tends to be slow, superficial, and predominantly seasonal (Hutchinson, 1978; Crozier, 1984; Alexander, 1993). They are long-term movements of non-increasing velocity, without well-defined sliding surfaces and such phenomenon occurs as rock creep, talus creeps, or soil creeps. Sometimes an initial creep achieves a critical acceleration causing serious damage, and as such, creep can be regarded as a preparatory stage for sliding, flow, or fall (Nemcok et al., 1972).

2.2 Previous workers

Geological studies in Nagaland, and landslides, in particular, are relatively sparse partly due to remoteness, inaccessibility, and other socio-political issues that have troubled the place for many decades. The oldest literature on the geology of Nagaland can be traced to Oldham (1883) who studied Kohima and parts of northern Manipur. Pascoe (1912) recorded the geology between Dimapur and Saramati areas. The Tertiary succession of Assam and Nagaland including the conditions of deposition and tectonics have been studied by Evans (1932) and Mathur and Evans (1964). Sondhi (1941) made the first attempt at a landslide study of Nagaland along the Dimapur-Manipur Road. Sharda and Bhambay (1980) prepared slope classification maps and geotechnical reports for Kohima town. Lotha (1994), Bhattacharjee et al. (1998), and Central Road Research Institute (CRRI, 2000a) worked on some landslides and weak zones in parts of NH 39, Kohima town, and the Maram area. Various research scholars, including Aier (2005), Walling (2005), Sothu (2009), Supongtemjen (2013), Jamir (2013), and Khalo (2016), Chang (2021) studied land instability in different places of Nagaland as part of their Ph.D. works. Kemas et al. (2004), Aier et al. (2005, 2009, 2011, 2012), Walling et al. (2005, 2016), Singh et al. (2008), Sothu et al. (2009, 2011), Jamir et al. (2011), Supongtemjen and Thong (2014), Supongtemjen et al. (2015), Khalo et al. (2016), Chang et al. (2021), Jamir et al. (2020, 2022) also carried out case studies on slope instability and contributed valuable information on landslides in the state.

2.3 Landslide causative factors

Landslides are mostly influenced by factors such as the slope angle, relief of the area, lithology, structure, drainage, intense and prolonged precipitation, anthropogenic activities, etc. However, in general, it is not appropriate to define the same list of these causative factors for all landslide in all the areas as the selection of these factors differ from place to place, depending on the scale of analysis, the characteristics of the study area, the landslide type and the failure mechanisms (Shano et al., 2020).

Slope

One of the most preferred input parameters by several researchers in landslide susceptibility studies is the slope (Mehrotra et al., 1992; Altin and Gokkaya, 2006; Dag, 2007; Yomralioglu, 2009; Hasekiogullari, 2011; Cellek, 2013; Süzen and Kaya, 2014; Budimir et al., 2015; Dölek and Avci, 2016; Duruturk et al., 2017; Cellek, 2020).

A great percentage of landslides (~81%) occurs in slopes that are greater than 30˚ (Terzaghi, 1950; Emelyanova, 1977; Aier, 2005). Slope is considered the most influential parameter in the formation and development of landslides, regardless of lithology, presence of structural features and the amount of water content, etc., It may occur on gentler slopes as well as the relationship of a slope with landslides could vary regionally, and it is therefore suggested that the slopes should be interpreted and evaluated with quantitative statistical methods (Van Westen, et al., 2003; Hasekiogullari, 2011; Supongtemjen, 2012; Cellek, 2020). Aspect can be described as the direction of a slope. The aspect of a slope may also play some role in the occurrence and number of incidences of landslides. Several workers have reported that the south-facing slopes receive more solar insolation, thereby enhancing the weathering process and leading to slope instability (Martha et al., 2011; Sarkar et al., 2013).

Relative relief

Relative relief refers to variation in height, which is the difference between the maximum height and minimum height of a given area. It represents the elevation difference between the ridge top and valley floor measured in the slope direction. Matula (1969) is of the opinion that the most important factor for slide initiation is the degree of relief. Lower elevation values indicate very little differential erosion in the area while the higher values indicate the presence of longitudinal or transverse faults passing through the area resulting in more erosional activities which in turn causes more instability. A terrain of higher elevations is more prone to landslides.

Lithology

The lithology of an area plays a key role in the stability of slopes. It has been widely recognized that lithology greatly influences the occurrence of landslides because lithological variations often lead to a difference in the strength and permeability of rocks and soils which are considered the most decisive parameters (Dai and Lee, 2002). The mineral assemblage and the strength of the constituent minerals are important criteria that affect stability as low-strength rocks tend to be fragile while strongly bonded rocks are more suitable for stability because weathering greatly reduces the shearing resistance of rocks (Piteau and Peckover, 1989).

Structure and lineaments

The physical and mechanical properties of rocks and slope stability are largely determined by the attitude and spatial distribution of planes of weakness. These may be primary and/or secondary discontinuities in rocks, such as bedding, fractures, foliations, joints, faults, shear zones, etc. Such planes greatly reduce the strength of rocks and, in turn, increase the probability of failure (Dai et al., 2002; Sarkar et al., 2013).

Lineaments are mappable, a linear feature of a surface whose parts are aligned in a slightly curvilinear or rectilinear relationship that reflects the subsurface phenomena (O'Leary et al., 1976). The impact of lineaments on landslides and their correlation has been studied by various researchers (Ramli et al., 2010; Yusof et al., 2011; Tsai et al., 2018) as various types of slope movements are often located close to linear features. Lineaments play an important role in the assessment of slope instability as the high degree of fracturing, and shearing makes the surrounding areas weak (Xu et al., 2012). Such areas become favorable for moisture accumulation, increasing the rate of weathering (Ali and Pirasteh, 2010) that affects surface structures and terrain permeability and thus exacerbating the problem of slope instabilities (Nagarajan et al., 1998; 2000; Gomez and Kavzoglu, 2005).

Drainage

Several studies have discussed the various effects of water on slope stability, and it is well known that one important contributor is drainage owing to the erosional activity of streams or saturation (Gökceoglu and Aksoy, 1996). The density and frequency of drainage in a unit area, therefore, play a vital role in this aspect. Poor drainage is often associated with higher landslide incidence as less surface runoff results in high infiltration and increased pore-water pressure (Kumar, 2005). Hence, proper drainage is a significant element in landslide mitigation measures (Korulla, 2020).

Land use/land cover

In recent times, Land use and land cover can be attributed to several landslide incidences. They control the rate of weathering and erosion, as activities like deforestation allow water to infiltrate the subsurface causing a reduction of the apparent cohesion of slope material with the gradual decay of tree roots at shallow depths and thereby inducing soil erosion and movement (Bishop and Stevens,1964; Swanston, 1974; Crozier and Vaughan,1990). Anthropogenic activities such as the construction of roads, rapid unscientific urban sprawl, and other developments associated with economic growth are attributed to the destabilization of hillsides, and the production of large volumes of debris thereby putting enormous stress even on the stable slopes (Ives,1987; Valdiya,1987; American Geophysical Union, 2021) and need to be studied in landslide susceptibility studies (Holcombe et al., 2016).

Rainfall

Rainfall is the most frequent landslide-triggering factor in many regions of the world (Corominas, 2001). Rainfall-induced landslides pose a substantial risk and have claimed an untold number of human lives and economic losses every year (Tohari, 2018). The highest incidences of landslides occur during and after relatively long periods and continuous rainfall. Severe storms, particularly those occurring in the rainy season and those that follow prolonged wet spells, are also attributed to some of the most damaging landslides in a region (Kemas et al., 2004; Thong et al., 2004; Aier, 2005).

Seismicity

Earthquake-induced landslides are potentially the most destructive hazards associated with earthquakes (Rodriguez et al., 1999) and are known for huge human casualties therefore, the role of seismicity as a triggering mechanism should be studied (Thigale, 1999). Many large slope failures have been triggered by earthquakes (Schuster and Highland, 2001) as well as related tectonic activities. Earth vibrations weaken slopes by reducing the factor of safety and thereby causing their failure.

2.4 Landslide Susceptibility, Vulnerability, and Risk Assessment (SVRA)

The Landslide Susceptibility, Vulnerability, and Risk Assessment (SVRA) studies are an integral part of a disaster management plan and are carried out not only to deduce the information on risks caused by a hazard in an area, but for developing the disaster risk reduction strategy through preparedness, prevention, response, and recovery. It is one of the prerequisites for the planning and further development of an area (Ram and Gupta, 2022).

2.4.1 Landslide Susceptibility mapping

In landslide susceptibility mapping, the preparation of a landslide inventory map is the first and foremost step and the most critical assessment criterion as it includes the basic information and landslide characteristics required to produce landslide susceptibility, vulnerability and risk maps (Can et al., 2019). A landslide inventory map primarily depicts the location, geographical extent, represents the spatial distribution, type and dimension of a landslide and provides the base for any landslide analysis (Wieczorek, 1984; Soeters and Van Westen, 1996) and therefore Landslide inventory map is an essential component for the preparation of an LSM. Landslide inventory maps are of significant importance in predicting the hazard for an area as the distribution of past movement provides a cue to the locations of future land sliding. Although there is no standardized method for the preparation of landslide inventory, historical data can be used along with satellite imagery, field surveys, and aerial photographs (Ayalew et al., 2005; Kanungo et al., 2006; Kayastha et al., 2012; Xu et al., 2014).

In the field of disaster management, the preparation of a Landslide Susceptibility Map (LSM) is a crucial step for any landslide study as it gives an overall perspective of landslide-prone areas. Brabb (1993) estimates that ~90% of landslide losses are avoidable if the problem is recognized before planning for developmental activities. Hence, it is important to categorize an area into zones according to its stability. An LSM delineates an area into homogeneous zones according to their degree of susceptibility to landslides, which may adversely affect the community and other elements. This assessment is vital for mitigation and community preparedness for landslide hazards.

Over the last few decades numerous methods have been used to evaluate landslide hazards (Van Westen, 1994; Carrara et al., 1995; Cruden & Fell, 1997; Guzzetti et al., 1999; Yilmaz, 2009; Sarkar et al., 2015; Sur et al., 2020). However, there is no consensus regarding the ideal method for preparing an LSM (Guzzetti et al., 2000). In most of the techniques, the input parameters are mostly the same but differ in the ranking of factors. In general, the methods are either based on the qualitative approach which dictates the assigning of weights to the factors based on experience and the expert's knowledge, or the quantitative approach which studies the relationship between existing landslides and the factors (Yalcin et al., 2011; Felicisimo et al., 2012; Peng et al., 2014; Wang and Li, 2017).

The qualitative approach is subjective in nature (Casagli et al., 2004; Fall et al., 2006; Kanungo et al., 2006; Raghuvanshi et al., 2014a; Girma et al., 2015) which involves direct mapping, where the causative factors are given ratings based on expert's knowledge and experience (Brabb et al., 1972; Wright et al., 1974; Van Westen et al., 2008). The quantitative approach is objective in nature (Fall et al., 2006; Girma et al., 2015) and are classified into deterministic, probabilistic, and statistical methods which rely on mathematical computations that have a less personal bias (Aleotti and Chowdhury 1999; Kanungo et al. 2009).

Quantitative methods have been widely used in recent times because it overcomes the subjectivity of the qualitative methods and is observed to provide more realistic results (Kanungo et al., 2009) as the Qualitative approach is associated with a certain degree of subjectivity in weight assignment procedures and uncertainty which is time-consuming, costly exercise and the scope of validation, in general, is absent or not followed (Aleotti and Chowdhury, 1999).

The deterministic method prepares LSM using mechanical laws with empirical methods (Selby, 1980; Romana, 1985; Anbalagan, 1992; Hack, 1998; Liu and Chen, 2007; Raghuvanshi, 2019), dynamic or static infinite slope modelling (Dietrich et al., 1995; Pack et al., 1998; Baum et al., 2002; Simoni et al., 2008), kinematic methods (Goodman, 1989; Kulatilake et al., 2011; Karaman et al., 2013; Zain Alabideen and Helal, 2016; Raghuvanshi, 2019), 2-D (Hoek and Bray, 1981; Sharma et al., 1995) and 3-D limit equilibrium and numerical modelling (Hungr and Rawlings, 1995; Stead et al., 2006; Gitirana et al., 2008; GEO-SLOPE, 2011; Karaman et al., 2013; Tang et al., 2016; Raghuvanshi, 2019). Deterministic techniques rely on the physical laws that defines the stability of a slope (Guzzetti et al., 2000) and require detailed data on geotechnical parameters. However, for the collection of such enormous data, the method is restricted only to site-specific, individual slopes and smaller areas (Aleotti and Chowdhury, 1999; Fall et al., 2006; Kanungo et al., 2009; Raghuvanshi et al., 2014a; 2014b).

The probabilistic method uses the probabilistic theory by comparing the spatial landslide distribution with the causative factors (explanatory variables), where the degree of relationship between the past landslide distribution and the causative factors are converted to a value based on a probability distribution function (Straub and Schubert, 2008; Kanungo et al., 2009; Lari et al., 2014). The probabilistic approach though quantitative however has a certain degree of subjectivity in the assignment of weights to causative factors. Therefore, the probabilistic approach is considered semiquantitative (Kanungo et al., 2006).

Statistical methods are further classified into Bivariate and Multivariate (Artificial Neural Network) methods and take into account the statistical relationship between slope instability and its causative factors (Carrara, 1983; Brand, 1988; Gupta & Joshi, 1990; Saha et al., 2005; Anbalagan et al., 2015; Chen et al., 2016). Bivariate methods are Weight of Evidence (WoE), Frequency Ratio, Information Value (InV), Yule Coefficient (Yc), Fuzzy Logic, and Distance Distribution analysis (Cárdenas & Mera, 2016; Shano et al., 2020). Multivariate methods are mainly Logistic Regression Model, Conditional Analysis, Artificial Neural Network, Multiple Regression Model, and Discriminant Analysis (Yin and Yan 1988; Van Westen, 1993; 1994; Chung and Fabbri, 1995; Guzzetti et al., 1999; Kanungo et al., 2006; Shano et al., 2020). Recently many algorithms of machine learning techniques are being used for LSM studies. However, state-of-the-art techniques such as Artificial Neural Network (ANN) and Decision Tree, usually consume longer processing time for data interpretation as compared to Bivariate statistical methods (Alkhasawneh et al., 2013a; 2013b; 2014a; 2014b). Also, the complexity in the elaboration of methodology in machine learning techniques often prevents or even makes their application to LSM studies difficult.

In the present study, three Quantitative statistical (Bivariate) methods viz. Yule Coefficient, Information Value, and Weight of Evidence have been used to quantitatively analyze the spatial correlation between landslides and multi-class factors because of its rapid computation and easy processing of data as compared to the various methods discussed above (Adeyemi, 2011).

Quantitative Bivariate Statistical method

One of the simplest forms of Quantitative (statistical) analysis is the Bivariate statistical method which involves the analysis of two variables often denoted as X and Y for the purpose of determining the empirical relationship between them (Pradhan et al., 2012). This method is based on the general assumption that "the past and present are key to the future" (Dai and Lee, 2001) which means the factors controlling the occurrence of landslides in an area in the past are the same as those that will cause landslides even in the future. Evaluation of these factors and their relation with the past landslides in an area helps in the prediction of future landslides (Dai et al., 2002; Lan et al., 2004; Girma et al., 2015; Chimidi et al., 2017).

The bivariate statistical analysis compares each data layer of causative factors to the existing landslide distribution and based on the landslide density of each factor, weights are assigned to the causative factors. They are simply the modified forms of the qualitative method, with the exception that weights are assigned based on the statistical relationship between past landslides and causative factor maps (Van Westen, 1994).

There are several advantages of using the bivariate method viz. the results obtained are highly efficient and accurate, straightforward execution of data, rapid computation of data, cost-effective, well perception of the landslides and its correlation with the causative factors (Süzen and Doyuran, 2003; Barbeiri and Cambuli. 2009; Huqqani et al., 2019)

2.4.1a *Yule Coefficient method*

The Yule Coefficient (Yc), also known as the Phi coefficient (Chedzoy 2004) has been used as a reliable measure of association between variables in the sciences, which is expressed as a dichotomy e.g., yes/no, presence/absence, and true/false (Adeyemi 2011). It calculates the spatial interrelation between the possible causative factors and landslides by assigning a weight that represents the strength of the association between the two (Yule, 1912; Fleiss, 1981; Bonham-Carter & Bonham-Carter, 1994; Komac and Zorn 2009). According to Adeyemi (2011), there are three advantages of using the Yc method, viz. it does not need corrections before/after data interpretation, it is quickly and easily computed, and it is a measure of the proportional association of one variable to another.

2.4.1b *Information Value method*

Another Bivariate statistical method is the Information Value (InV) method which is developed from Information theory by Yin and Yan (1988) and modified by Van Westen (1993) and Sarkar et al. (2006). It determines the degree of influence of causative factors responsible for the occurrence of landslides in an area. Due to its simplicity and cost-effectiveness in data computation, it has been widely used for LSM studies (Yin and Yan, 1988; Jade and Sarkar, 1993; Lin and Tung, 2003; Zêzere et al., 2004; Saha et al., 2005; Yalcin, 2008; Kanungo et al. 2009; Balasubramani and Kumaraswamy, 2013; Abidine and Abdelmansour, 2019; Mengistu et al., 2019; Sarda and Pandey, 2019; Genene and Meten, 2021).

2.4.1c *Weight of evidence method*

The Weight of Evidence (WoE) method is proposed by Frederik Pieter Agterberg, a Canadian mathematical geologist in 1980. It was first developed for the study of medical diagnostics to investigate and discover certain diseases (Lusted, 1968). Its application extended to several researchers working in the field of landslide susceptibility assessment (Van Westen et al., 2003; Lee et al., 2004; Lee and Talib, 2005; Lee and Sambath, 2006; Pradhan et al., 2010).

A data-driven method based on Bayes theorem (Bayesian method), it is a log-linear form of the Bayesian probability model that drive prediction outputs using landslide occurrence as a training point (Mersha and Meten, 2020). It calculates the degree of spatial association between predictive variables of a phenomenon (causative factors of a hazard) and the dependent variable of this phenomenon (hazard), assigns weights to them, and then uses a mathematical summation technique to summarize the weighted factor maps into a final map (Bousta and Brahim, 2018).

The advantage of using the WoE method is its accuracy, efficiency, reliability, and cost-effectiveness (Bonham-Carter, 2002; Luliana, 2012; Roering and Josh, 2012).

2.4.1 d Validation of LSM

The LSM can be validated in several ways (Chung & Fabbri, 1999, 2003; Lee & Min, 2001; Fabbri et al., 2003; Lee, 2007; Lee & Pradhan, 2007; Pradhan et al., 2010). For the statistical methods, the best approach is the application of the Success Rate Curve or Area Under the Curve (AUC) (Chung & Fabbri, 1999). This application measures the accuracy of the susceptibility map in classifying the area of existing landslides as susceptible areas. The AUC may be calculated with a hypothetical validation curve coinciding with a diagonal ranging from 0.5 to 1 (Remondo et al., 2003; Lee, 2007). The test result is considered accurate if AUC is near one (1), and fair if it is near 0.5 (Das et al., 2010). The analysis is validated in the field to ascertain the accuracy of the generated LSM.

2.4.2 Landslide Vulnerability Assessment (LVA)

There is no universal method for assessing the vulnerability of an area (Fuchs et al. 2011). According to Varnes (1984) and Papathoma-Kohle et al. (2015), LVA is a key component of Landslide Risk Evaluation (LRE). For several decades, there has been a lot of debate regarding the definition of "Vulnerability", since scientists of different scientific fields have used this term in numerous ways (Glade, 2003; Füssel, 2007; Fuchs, 2009; Hufschmidt and Glade, 2010; Birkmann et al., 2013; Ciurean et al., 2013). However, in natural science, Vulnerability is defined as "the degree of loss for an element at risk as a consequence of a certain event, resulting from the occurrence of a natural phenomenon of a given magnitude"). It is expressed on a scale from 0 to 1, where, 0 = no damage; 1 = total damage.

The extreme complexities in vulnerability assessment, such as the velocity and impact angle of the landslide, the position of the wall impact point (settlement), the detailed geometry of the settlement, and the strength of the material affect the landslide vulnerability, making it difficult and time consuming to collect all these data which in turn leads to the literature on vulnerability assessment rare and limited (Glade, 2003; Li et al., 2010).

2.4.3 Landslide risk evaluation

Risk can be defined as the probability of harmful consequences, such as expected losses, death, injury, disruption of economic activity or social systems, and damage to property and the environment. It is the consequence of the interaction between a hazard and the characteristics that make people and places vulnerable and exposed. The level of risk, therefore results from the intersection of hazard with the elements at risk by way of their vulnerability (Glade et al., 2005).

Landslide risk evaluation is undertaken after evaluating the landslide susceptibility and vulnerability of an area (Wu et al., 1996). Varnes (1984) established that the main objective of landslide risk evaluation is to determine the expected degree of loss due to a landslide i.e., the expected number of lives lost, people injured, damage to property, and disruption of economic activity. Therefore, a vulnerability assessment is carried out for each element at risk with respect to the hazard.

Wadhawan S K, 2015 opine that LRE is the whole gamut of all exercises in landslide studies starting from i.) identification of landslide-affected areas (landslide inventory), ii.) knowing its susceptibility (predictions of spatial locations), iii.) elements at risk (vulnerability assessment) followed by iv.) risk evaluation and v.) to implement ground-level actions towards mitigation and reduction of the risk.

CHAPTER 3

METHODOLOGY

A subset of the study area consisting of the present town settlement and some portions of the surrounding areas was delineated using Google Earth imagery. Fieldworks were carried out in and around Noklak town to map the unstable areas, lithology, land use and land cover, geological structures, and also to validate the information derived from the satellite images. Global Positioning System (GPS) was used to mark the waypoints, a digital camera and a DGI Phantom Pro+ drone was employed for photography of the study area, geological hammer, chisels, measuring tape, scale, and field notebook, etc., were utilised for collection of data. Altogether, twenty-six (26) unstable areas identified in the field were marked by the GPS and digitized in GIS to prepare the landslide inventory map.

3.1 Landslide Susceptibility Mapping

3.1.1 Landslide inventory

In the present study, landslide inventory (26 in total) covering a total area of 0.82 km^2 (8116 pixels) of the study area (4.24 km^2 i.e, 42369 pixels) was delineated using Google Earth imagery and Bing imagery each of 1.0-2.5 m resolution, along with detailed field surveys using a Global Positioning System (GPS). The landslide datasets were then rasterized and resampled into grid sizes of 10x10 m resolution in ArcGIS 10.7 software.

3.1.2 Preparation of Landslide Susceptibility Map

The LSM is prepared in the laboratory using the ArcGIS 10.8 software (Fig. 3), where each causative factor map is combined with the landslide inventory map, and weighting values based on landslide densities are calculated for each of the parameter classes based on the formulas given by different bivariate methods. In order to quantify the spatial probability of landslides, three Quantitative Bivariate Statistical methods are adopted, viz. Yule coefficient (Yc) method, Information Value method (InV), and Weight of Evidence method (WoE).

For the susceptibility analysis, the spatial database and thematic maps of the landslide causative factors, including the elevation, slope, aspect, lineament, drainage, road, lithology, land use and land cover were prepared. The maps were then rasterized and resampled into grid sizes of 10x10 m resolution, and the association between landslide occurrences and each causative factor was analyzed. From the Inventory map, 20 unstable areas (80%) were randomly selected for preparing a landslide susceptibility map, and the remaining 6 landslides (20%) were used to validate the accuracy of the map.

A CARTOSAT image was utilized to get the topographic data that is used in the analysis (slope, aspect, and elevation) from the Digital Elevation Model (DEM) and also to prepare the lineament map (Table 3.1a). Nine categories of lineament buffers were demarcated from the lineament map. The Drainage and the road network map were prepared with the help of satellite imagery, and five categories of drainage buffers and nine categories of road network buffers were built. The land use land cover map was prepared by comparing data from LISS IV, Bing, and Google earth imageries. The lithological map was prepared from the field information and then digitized. The details of the parameters used as input for landslide susceptibility mapping are given in table 3.1b.

Using ArcGIS 10.8 and ILWIS 3.3 software, three (3) separate LSMs are prepared by employing the Yule coefficient (Yc) method, the Information Value method (InV), and the Weight of Evidence method (WoE). The particular map having the highest accuracy is then chosen for Landslide Risk evaluation.

Table 3.1a: Details of the various satellite imagery of the study area used

Satellite data / Source	**Date acquired**	**Spatial resolution**
Google Earth (GE) imagery	2018	1.0-2.5 m
Bing imagery	2018	1.0-2.5 m
Cartosat-1 / ISRO	2009	2.5 m
LISS-4 / ISRO	2018	5.8 m

Table 3.1b: Details of thematic layers used in the study and their sources

Sl. No.	**Parameters**	**Definition**	**Source**	**Resolution (m)**
1	Elevation	Height of the area above mean sea level	DEM (CARTOSAT-1 stereo data)	10
2	Slope angle	Ratio of altitude change to the horizontal distance	DEM (CARTOSAT-1 stereo data)	10
3	Slope aspect	Slope azimuth	DEM (CARTOSAT-1 stereo data)	10
4	Lithology	Gross physical characteristics of a rock or rock formation	Field studies	10
5	Proximity to lineament	Mappable, linear features on the surface caused by	Digitized lineament layer (IRS-P5, CARTOSAT-1,	10

		drainage, faults, lithological condition, etc.	IRS-P6 LISS-IV & GE image)	
6	Proximity to drainage	Streams and river channels	Digitized drainage layer (CARTOSAT-1 and IRS-P6 LISS-IV & GE images and SoI topographic map)	10
7	Proximity to road	Slopes cut for transportation	Digitized drainage layer (CARTOSAT-1 and IRS-P6 LISS-IV & GE images and SoI topographic map)	10
8	Land use/Land cover	Human utilization of land / Physical material on earth's surface	IRS-P6, LISS-IV & GE images	10

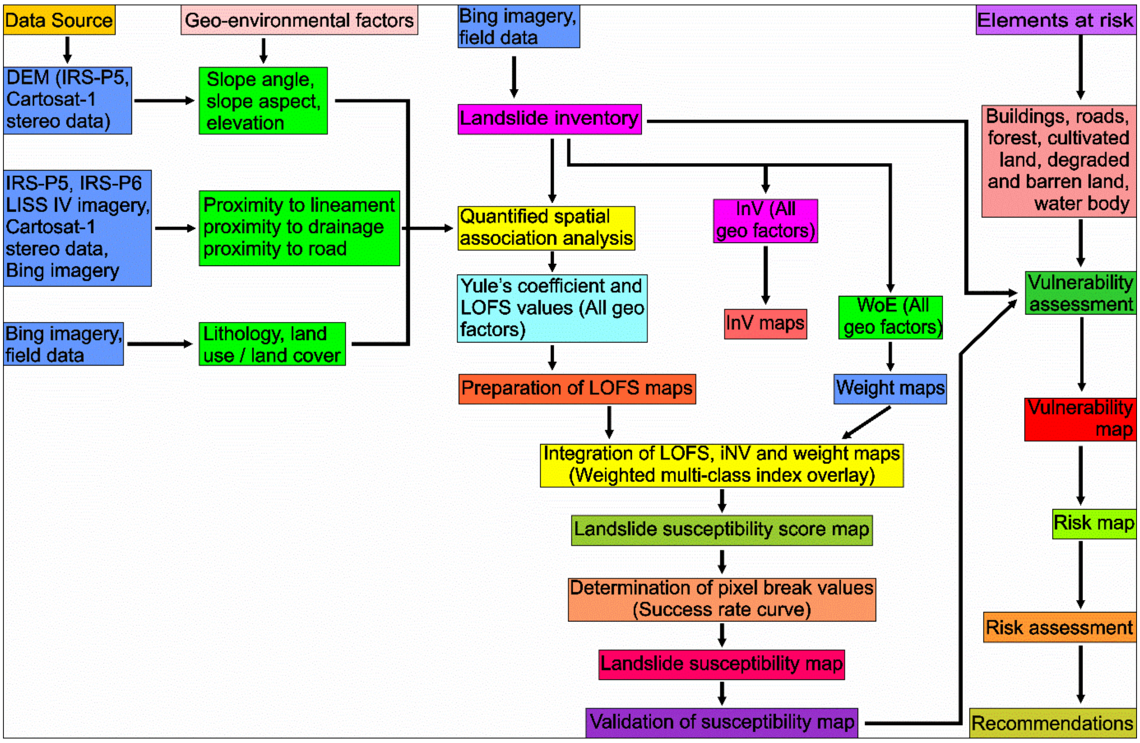


Fig. 3. Flowchart of the methodology

3.1.3 Yule coefficient method (YC)

The YC value is calculated using the following equation:

$$Yc = \frac{\sqrt{\frac{T11}{T21}} - \sqrt{\frac{T12}{T22}}}{\sqrt{\frac{T11}{T21}} + \sqrt{\frac{T12}{T22}}} \qquad \ldots 1$$

Where, T_{11} = Area where both the factor class and landslides are present

T_{12} = Area where the factor class is absent but landslides are present

T_{21} = Area where the factor class is present but landslides are absent

T_{22} = Area where neither the factor class nor landslides are present

The Yc values range from -1 to +1, which indicates negative and positive spatial associations, respectively (Yule, 1912). Based on these values, the landslide occurrence favorability score (LOFS) is calculated using the following equation (Eq 2), which represent the relative influence of each factor on landslide occurrence.

$$\text{LOFS} = \begin{cases} 0 & for \quad Yc \leq 0 \\ Yc/_{Ycmax} & for \quad Yc > 0 \end{cases} \qquad \dots 2$$

Using the Yc values, the Inter-predictor (Int. wt) weights are calculated. Here, the absolute difference value is first calculated using the maximum and minimum Yc values using the formula:

Absolute difference (Abs diff) = Maximum Yc-Minimum Yc, … 3

The Inter-predictor is then calculated with the formula:

Int. wt = Abs diff of causative factor xyz / Minimum value of Abs diff value from amongst all the causative factors … 4

3.1.3a Preparation of landslide susceptibility score map

The susceptibility score map is prepared using the map algebra expression:

Susceptibility score = (LOFS slope x Int.wt of slope + LOFS aspect x Int.wt of aspect + LOFS elevation x Int.wt of elevation + LOFS LULC x Int.wt of LULC + LOFS lithology x Int.wt of lithology + LOFS lineament x Int.wt of lineament + LOFS road x Int.wt of road + LOFS drainage x Int.wt of drainage) / Total Int.wt of all causative factors. … 5

3.1.3b Preparation of success rate curve and LSM

The success rate curve is prepared using the landslide inventory map and susceptibility score map with the X axis as percmap (percentage of map) and Y axis as percensld (percentage of landslide). Here, the pixel value that falls at 70% of percensld with respect to the percmap will determine the upper boundary of moderate susceptibility or the pixel boundary value between moderate and high susceptibility zones. Similarly, the pixel value at 90% of percensld with respect to the percmap marks the upper boundary of low susceptibility.

Finally, the landslide susceptibility map is prepared by using the susceptibility score map as an input raster in Arc GIS to classify the study area into different susceptible areas.

3.1.4 Information Value method (InV)

The InV is calculated using the following equations:

Inv = ln (Conditional probability (CP))/Prior Probability (PP)) …6

= (Nslpix/Ncpix)/(Ntslpix/Ntcpix)

Where,

Conditional probability (CP) = Ratio of the pixel of a landslide in class to the pixel of a class

Prior probability (PP) = Ratio of the total number of pixels of landslide to the total number of pixels of the study area.

Nslpix = Landslide pixel/area in a factor class

Ntslpix = Total area of landslide in the study area

Ncpix = Area of the class in the study area and

Ntcpix = Total pixel area in the study area

Landslide Susceptibility score map = (InV x Slope InV + InV x Aspect InV + InV x Proximity to drainage InV+ InV x Lithology InV + InV x LULC InV + InV x Proximity to lineament InV + InV x Proximity to road InV + InV x Elevation) …7

When InV > 0.1, the landslide occurrence with the factor classes has a high correlation and will have a high probability of landslide occurrence. When InV < 0.1 or InV < 0, it signifies a low correlation between landslide factors and landslide occurrence, indicating a low probability of landslide occurrence.

The landslide susceptibility score map is prepared by adding the weighted Inv values with Inv maps. The procedure for preparation of the success rate curve and the LSM is the same as the one followed in the Yc method.

3.1.5 Weight of Evidence method (WoE)

The WoE method is based on the calculation of positive and negative weights to define the degree of spatial association between each variable class and landslide occurrence (Pardeshi et al., 2013). The positive weights (W+) indicate the occurrence of a landslide event, while negative weights (W-) indicates the non-occurrence of an event. To evaluate the W+ and W-, calculating the following parameters is important:

Nmap = total number of pixels in the map

Nslide = total number of pixels with landslides in the map

Nclass = number of pixels in the class

NSLclass = number of pixels with landslides in the class

The values required for the weight of evidence formula are:

Npix1 = NSLclass

Npix2 = Nslide – NSLclass

Npix3 = Nclass – NSLclass

Npix4 = Nmap – Nslide – Nclass + NSLclass

Then the positive and negative weights are calculated from the ratios of the natural logarithms by the formulas (Bonham-Carter, 1994; Elmoulat et al., 2015):

$$W^{+} = Ln \frac{\frac{Npix_1}{Npix_1 + Npix_2}}{\frac{Npix_3}{Npix_3 + Npix_4}}$$

$$W^{-} = Ln \frac{\frac{Npix_2}{Npix_1 + Npix_2}}{\frac{Npix_4}{Npix_3 + Npix_4}}$$

…8

Where,

Npix1 = landslide pixels present on a given factor class,

Npix2 = landslides pixels not present in a given factor class,

Npix3 = number of pixels in a given factor class in which no landslide pixels are present,

Npix4 = number of pixels in which neither landslide nor the given factor is present. (Van Westen, 2002; Dahal et al., 2008; Regmi et al., 2010).

These +ve and -ve weights are then used to calculate the weight of contrast value (C) for the particular susceptibility variable to define the significance of the overall spatial association between the landslide causative factors and the landslide distribution (Dahal et al., 2008). This is then calculated as the difference of positive and negative weights (Ozdemir, 2011) with the formula to determine the contrast value (C)

C = (W+) − (W−) …9

If the C value is positive, it will have a positive spatial association, while the negative value will signify a negative spatial association. The weighted map (Wmap) for each causative factor is prepared by adding the weights of contrast(C) values of each factor class (Equation 7). Finally, the LSM is prepared by adding all the weighted maps (ΣW map) of each landslide causative factor with a raster calculator and map algebra in the spatial analyst tool of ArcGIS (Equation 7).

ΣW map = ΣC …10

LSI = ΣW map …11

The same procedure used in the Yc method is also followed here for building the success rate curve and the LSM.

3.1.6 Validation of LSM

The 3 LSMs prepared by employing the different methodologies are then validated using the Area Under Curve analysis. The AUC is calculated using the tool "Calculate ROC curves and AUC values" from the ROC tool under the ArcSDM toolbox in the Arc GIS software.

3.2 Landslide Vulnerability Assessment (LVA)

In this study, the vulnerability is evaluated by determining the degree of damage for each element at risk from the landslide hazard using the vulnerability scale (UNDRO, 1984; Varnes and IAEG, 1984; Fell, 1994). It can be mathematically expressed as:

$$V = E \times H \qquad \dots 9$$

Where, V- Vulnerability, E-Elements at risk and H-Hazard

The elements at risk from landslides vary from place to place. Noklak is a small town devoid of major industries or offices, and therefore only six components were identified as significant for the study. The elements are buildings, population, roads, forests, water bodies, and barren land. A total of 2048 buildings were digitized in Arc GIS from Google Earth imagery and validated in the field. The population parameter was calculated by multiplying the total number of buildings digitized (2048) by 5.5. The value 5.5 is derived by dividing the total population by the total households as per the last census, i.e. 7674/1384. The road network was digitized in Arc GIS using Google Earth imagery. Forest areas, water bodies, and barren land were identified and digitized using LISS-IV and Google earth imageries and later verified in the field.

3.3 Landslide risk evaluation

Risk is a function of hazard and vulnerability (Varnes and IAEG, 1984; Anbalagan and Singh, 1996). The Landslide risk of the study area is calculated by using the mathematical expression**:**

$$R = f\,(H \times V) \qquad \dots 10$$

Where, H- Hazard, and V - Vulnerability

CHAPTER 4

RESULTS

4.1 Landslide Susceptibility Mapping

The thematic maps, Viz., the Inventory map, elevation, slope, aspect, lineament, drainage, road, lithology, land use and land cover constituting the landslide causative factors, are prepared.

Thematic Mapping of Causative factors

The instabilities in the area are predominantly subsidence zones and some are sliding areas of differing magnitude. Amongst the 26 unstable areas identified, a landslide situated at the western part of the township had a major impact. It started as a minor landslide in 1980 and has been active for the last four decades growing into a major unstable zone affecting an area of 0.74 km^2, nearly one-fourth of the township. This major landslide has adversely affected roads, human settlements and agricultural tracts. Another landslide located at the eastern portion of the town is also rapidly growing, covering an area of 0.23 sq.

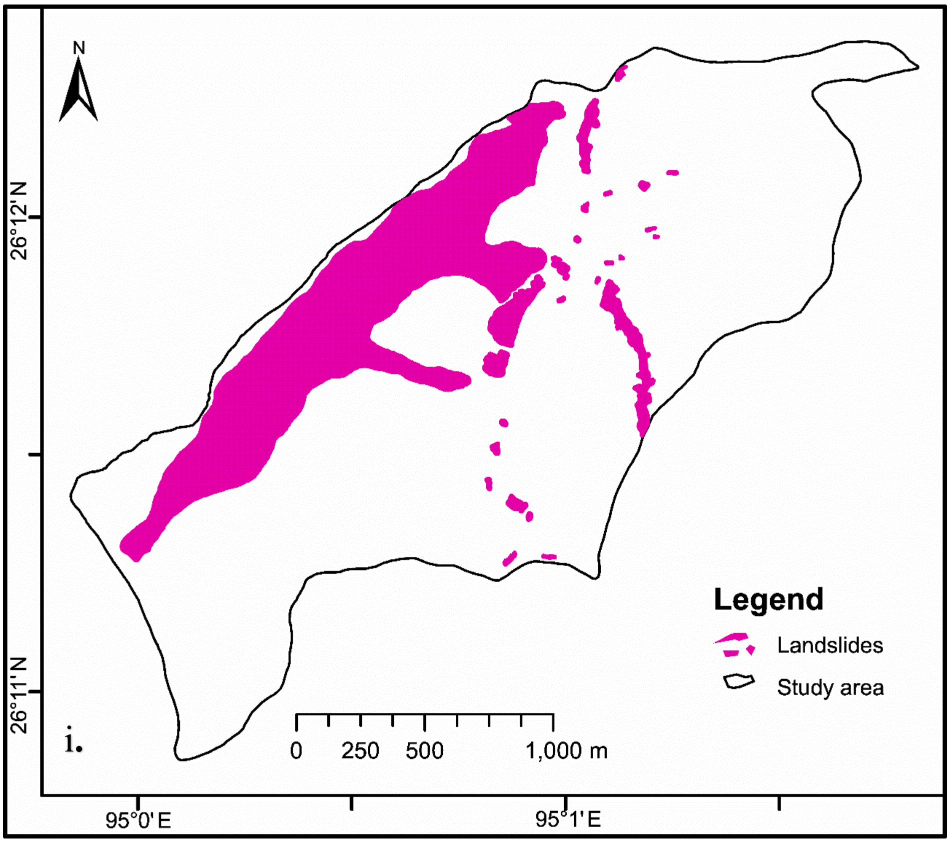


Fig. 4.1 (i.) Landslide inventory map of the study area

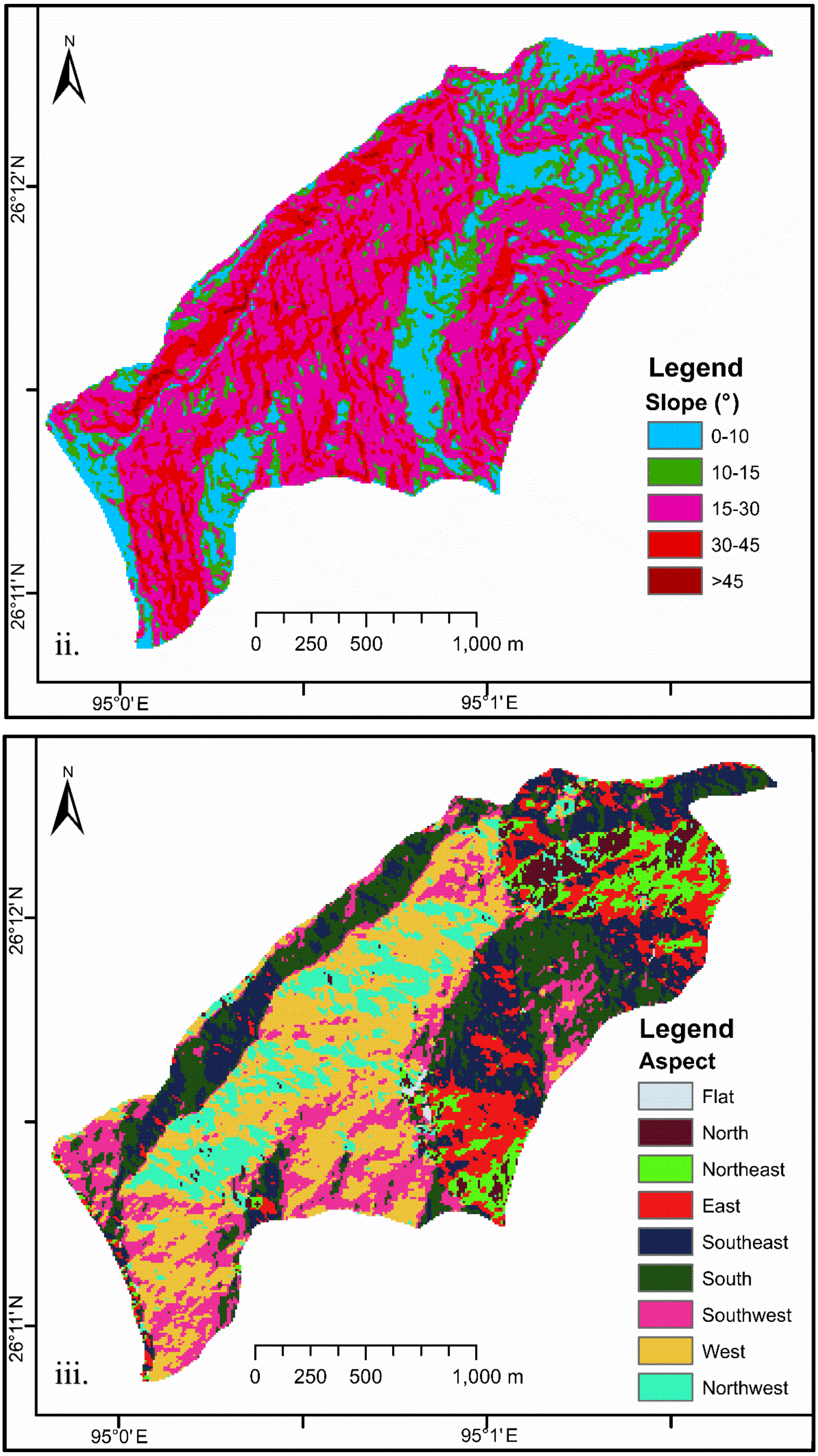
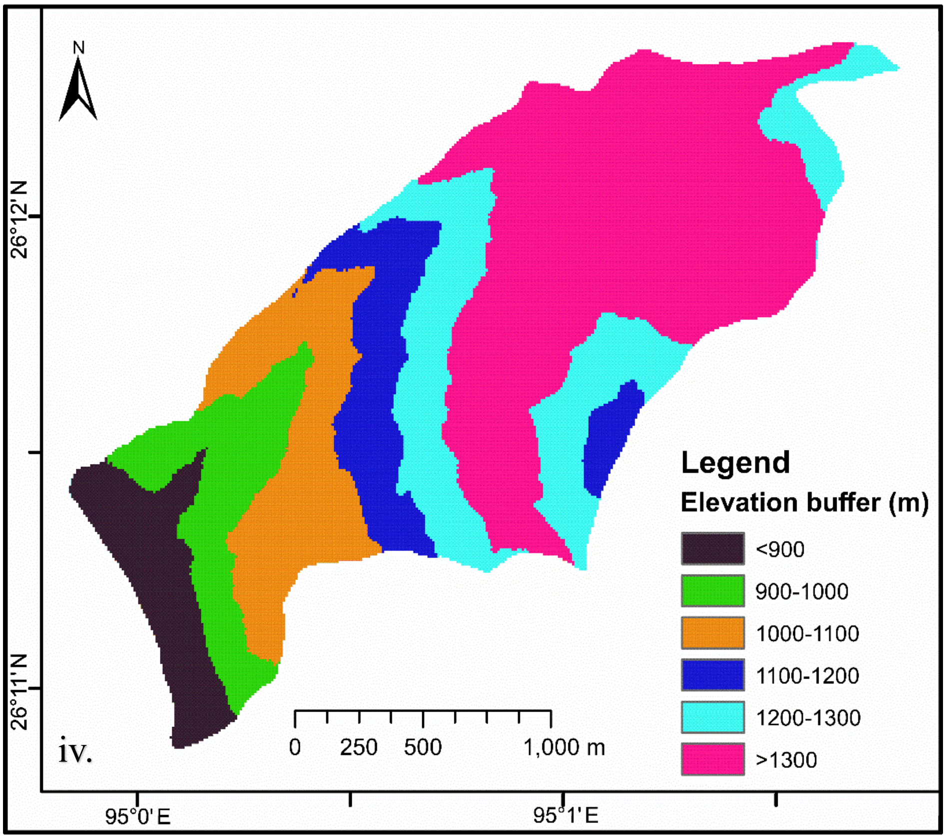


Fig 4.1. Thematic maps of the study area ii.) Slope iii.) Aspect



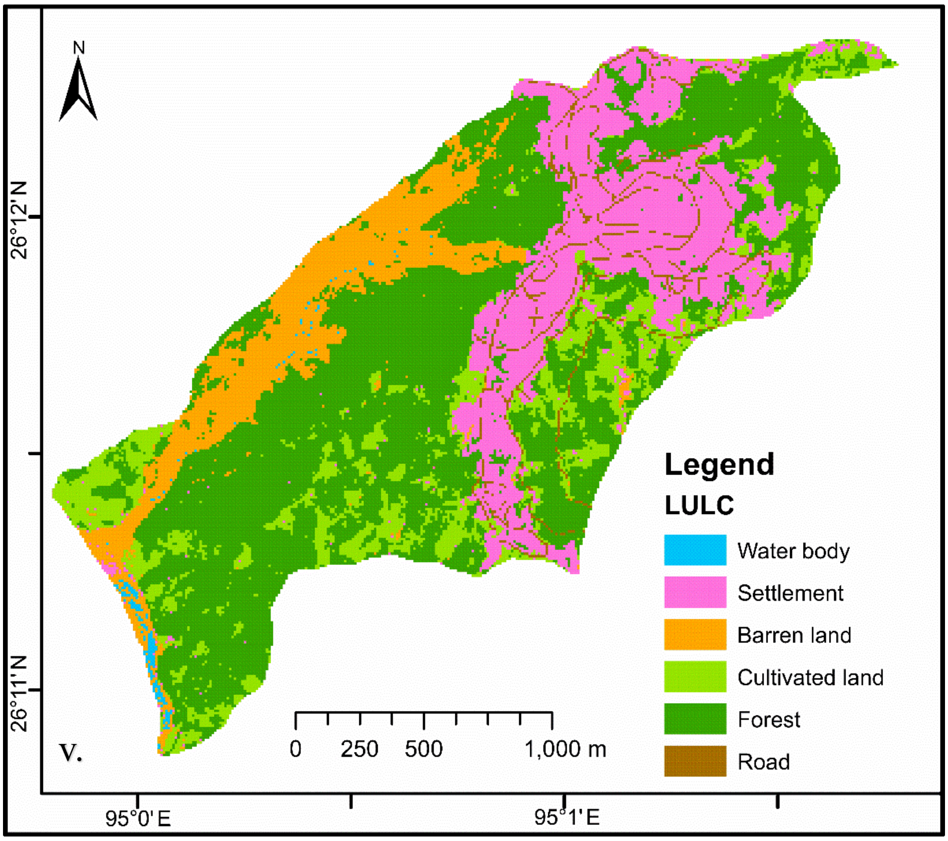


Fig 4.1. Thematic maps of the study area iv.) Elevation v.) LULC

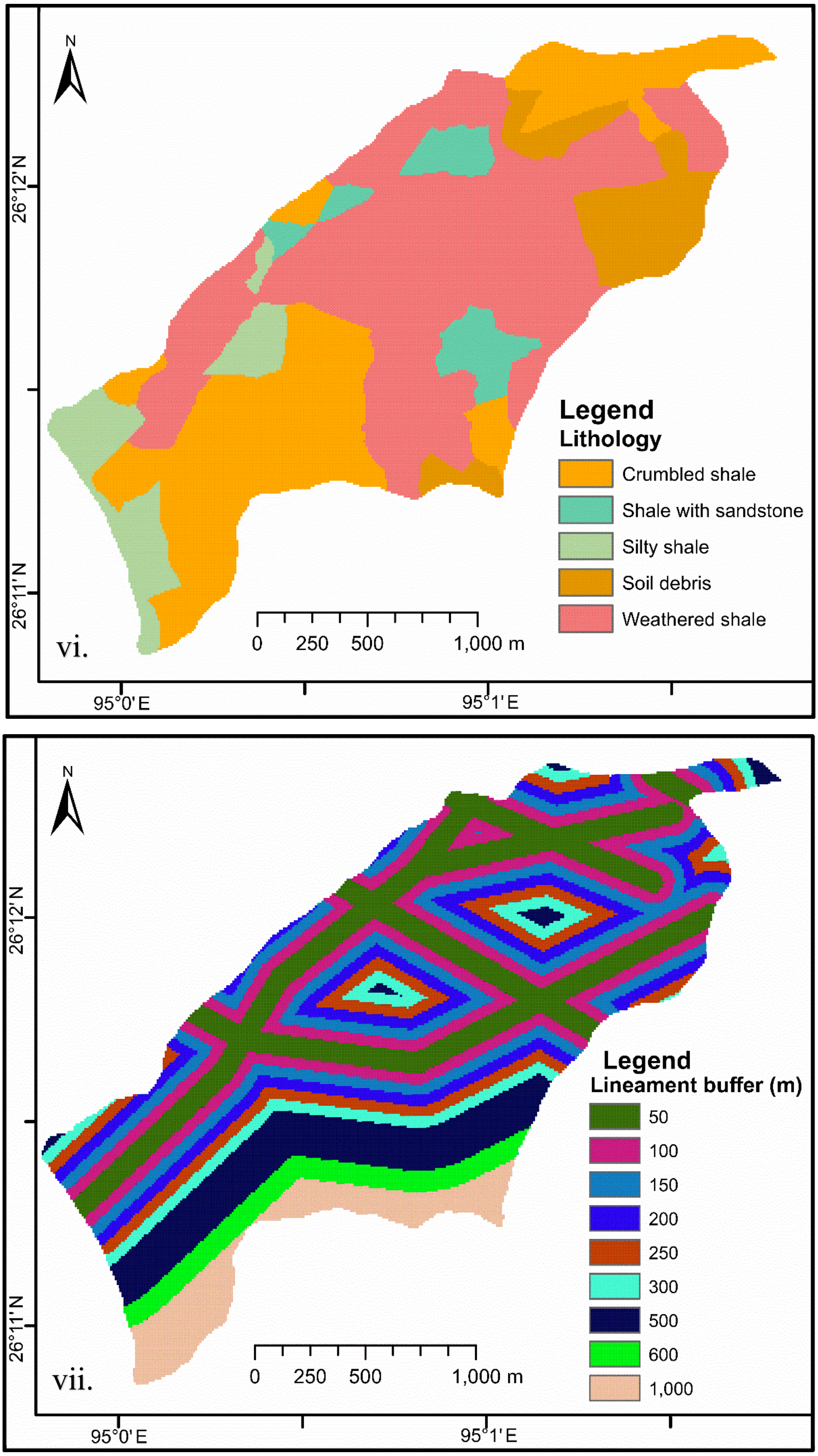


Fig 4.1. Thematic maps of the study area vi.) Lithology vii.) Lineament

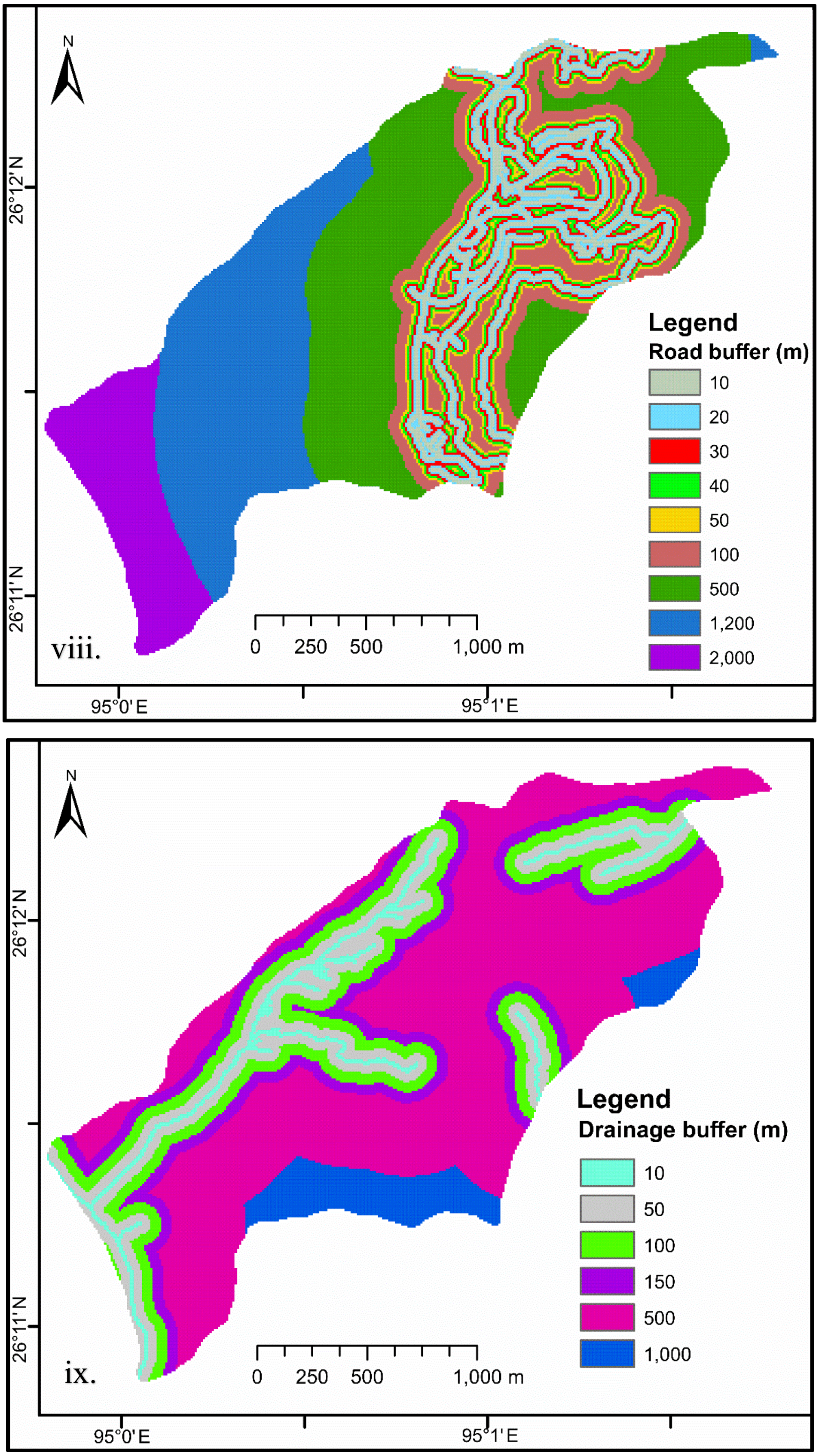


Fig 4.1. Thematic maps of the study area viii.) Road ix.) Drainage

4.1.1 Yule Coefficient method (Yc)

The Landslide Occurrence Favourability Score maps are built by superimposing the thematic maps of the causative factors with the inventory map to estimate the interrelationship between landslides and each factor using the Yc method.

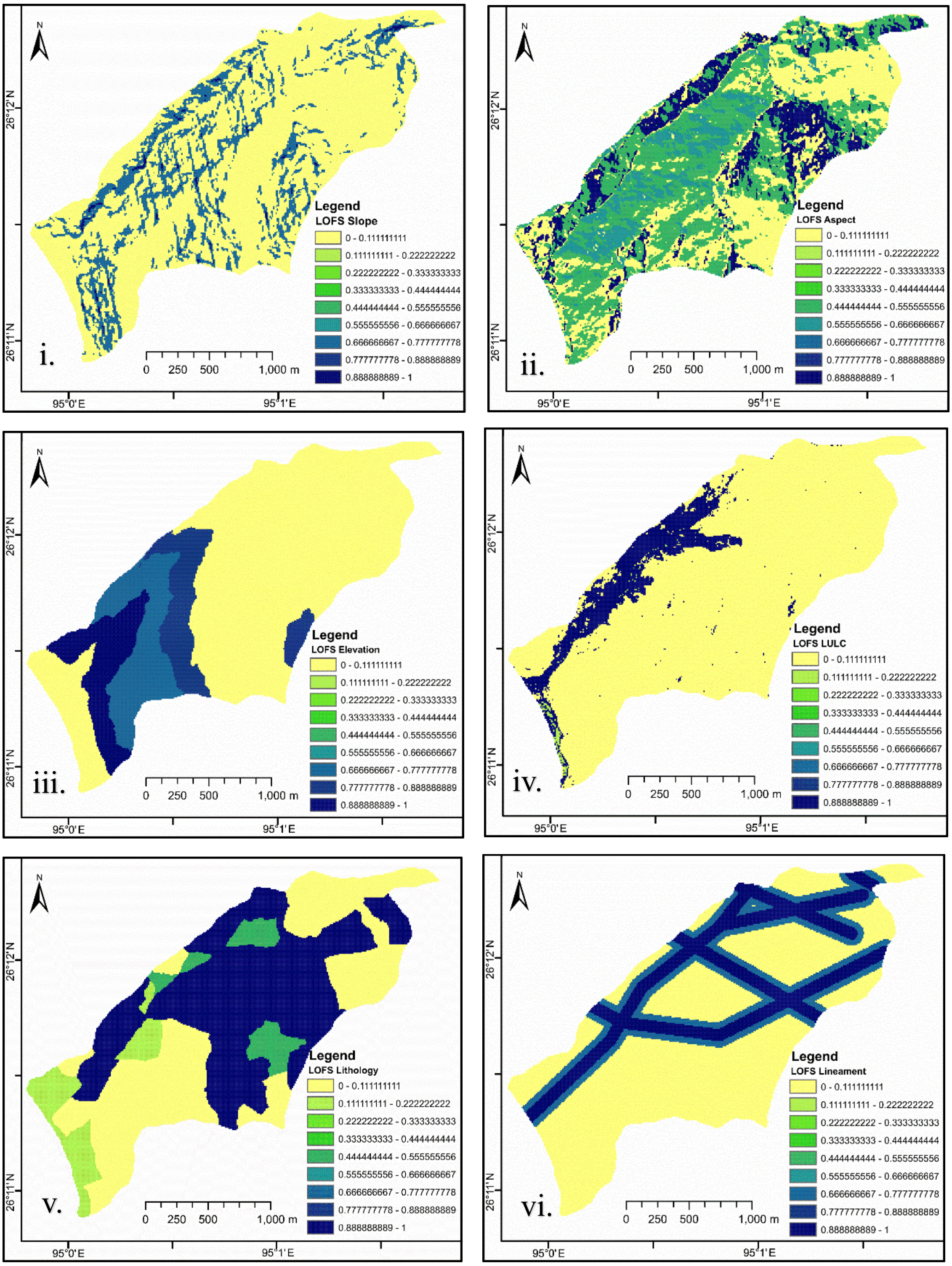


Fig 4.1.1. LOFS maps of the study area i.) Slope ii.) Aspect iii.) Elevation iv.) Land Use Land Cover v.) Lithology vi.) Lineament

Table 4.1.1a: Computed ratios for classes of various data layers based on landslide occurrences:

Slope									
Class (degree)	NpixC	NpixT	T11	NpixLS	T12	T21	T22	YC	LOFS
0-10	6235	42369	525	8116	7591	5710	28543	-0.26	0.00
10-15	6096	42369	668	8116	7448	5428	28825	-0.18	0.00
15-30	20943	42369	4076	8116	4040	16867	17386	0.01	0.04
30-45	8673	42369	2670	8116	5446	6003	28250	0.21	0.75
>45	422	42369	177	8116	7939	245	34008	0.28	1.00

Aspect									
Name	NpixC	NpixT	T11	NpixLS	T12	T21	T22	YC	LOFS
Flat	115	42369	5	8116	8111	110	34143	-0.39	0.00
North	835	42369	11	8116	8105	824	33429	-0.62	0.00
North East	2327	42369	14	8116	8102	2313	31940	-0.73	0.00
East	4117	42369	126	8116	7990	3991	30262	-0.49	0.00
South East	6572	42369	1579	8116	6537	4993	29260	0.09	0.47
South	6554	42369	1986	8116	6130	4568	29685	0.18	1.00
South West	6587	42369	785	8116	7331	5802	28451	-0.16	0.00
West	10576	42369	2502	8116	5614	8074	26179	0.09	0.50
North West	4147	42369	1082	8116	7034	3065	31188	0.11	0.61
North	539	42369	26	8116	8090	513	33740	-0.37	0.00

Elevation									
Class	NpixC	NpixT	T11	NpixLS	T12	T21	T22	YC	LOFS
<900	3293	42369	431	8116	7685	2862	31391	-0.12	0.00

900-1000	4081	42369	1490	8116	6626	2591	31662	0.25	1.00
1000-1100	5442	42369	1604	8116	6512	3838	30415	0.17	0.67
1100-1200	4150	42369	1359	8116	6757	2791	31462	0.20	0.82
1200-1300	7664	42369	1399	8116	6717	6265	27988	-0.02	0.00
>1300	17739	42369	1833	8116	6283	15906	18347	-0.27	0.00

LU/LC									
Name	NpixC	NpixT	T11	NpixLS	T12	T21	T22	YC	LOFS
Water body	186	42369	54	8116	8062	132	34121	0.14	0.19
Settlement	8537	42369	459	8116	7657	8078	26175	-0.39	0.00
Barren land	5196	42369	4302	8116	3814	894	33359	0.73	1.00
Cultivated land	6197	42369	203	8116	7913	5994	28259	-0.48	0.00
Forest	21190	42369	3028	8116	5088	18162	16091	-0.16	0.00
Road	1063	42369	70	8116	12132	993	9710	-0.62	0.00

Lithology									
Name	NpixC	NpixT	T11	NpixLS	T12	T21	T22	YC	LOFS
Crumbled shale	12844	42369	738	8116	7378	12106	22147	-0.40	0.00
Silty shale	3497	42369	753	8116	7363	2744	31509	0.04	0.12
Weathered shale	19449	42369	5829	8116	2287	13620	20633	0.33	1.00
Shale with sandstone	2454	42369	774	8116	7342	1680	32573	0.18	0.54
Soil debris	4125	42369	22	8116	8094	4103	30150	-0.75	0.00

Lineament									
Distance (m)	NpixC	NpixT	T11	NpixLS	T12	T21	T22	YC	LOFS
50.00	8703	42369	3278	8116	4838	5425	28828	0.31	1.00
100.00	7415	42369	2371	8116	5745	5044	29209	0.21	0.69

150.00	6594	42369	1286	8116	6830	5308	28945	0.01	0.02
200.00	5121	42369	850	8116	7266	4271	29982	-0.05	0.00
250.00	3061	42369	170	8116	7946	2891	31362	-0.35	0.00
300.00	2135	42369	55	8116	8061	2080	32173	-0.51	0.00
500.00	4471	42369	85	8116	8031	4386	29867	-0.58	0.00
600.00	1958	42369	9	8116	8107	1949	32304	-0.76	0.00
1000.00	2911	42369	12	8116	8104	2899	31354	-0.78	0.00

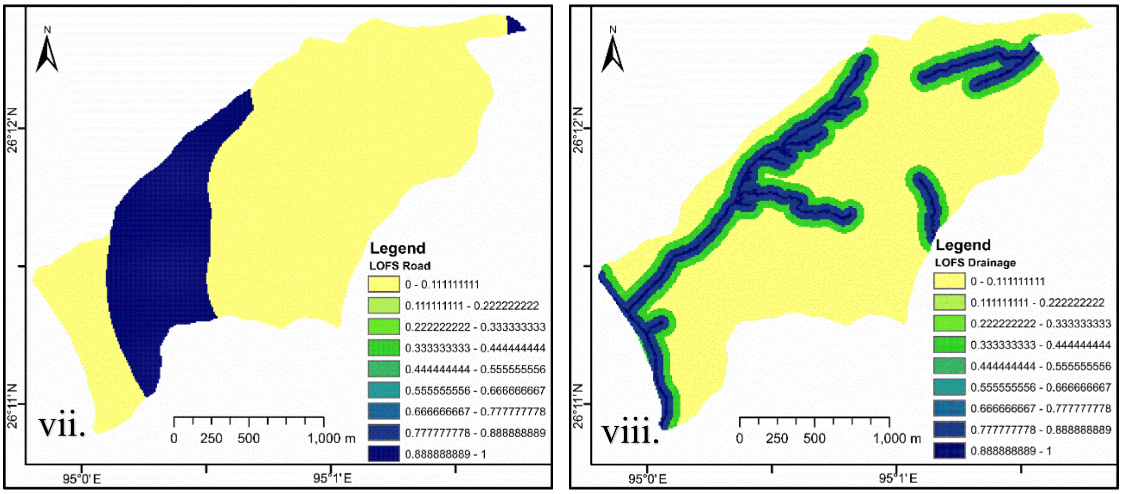


Fig 4.1.1. LOFS maps of the study area vii.) Road viii.) Drainage

Table 4.1.1a: Computed ratios for classes of various data layers based on landslide occurrences:

Road									
Distance (m)	NpixC	NpixT	T11	NpixLS	T12	T21	T22	YC	LOFS
10	3133	42369	176	8116	7940	2957	31296	-0.35	0.00
20	2771	42369	163	8116	7953	2608	31645	-0.33	0.00
30	2315	42369	121	8116	7995	2194	32059	-0.36	0.00
40	1837	42369	80	8116	8036	1757	32496	-0.40	0.00
50	1496	42369	63	8116	8053	1433	32820	-0.41	0.00
100	4293	42369	263	8116	7853	4030	30223	-0.33	0.00
500	12001	42369	2770	8116	5346	9231	25022	0.08	0.23

1200	9879	42369	3949	8116	4167	5930	28323	0.36	1.00
2000	4644	42369	531	8116	7585	4113	30140	-0.17	0.00

Drainage									
Distance (m)	NpixC	NpixT	T11	NpixLS	T12	T21	T22	YC	LOFS
10	1578	42369	988	8116	7128	590	33663	0.48	1.00
50	5642	42369	2802	8116	5314	2840	31413	0.41	0.87
100	5919	42369	1919	8116	6197	4000	30253	0.21	0.44
150	5502	42369	1163	8116	6953	4339	29914	0.04	0.07
500	20724	42369	1224	8116	6892	19500	14753	-0.46	0.00
1000	3004	42369	20	8116	8096	2984	31269	-0.72	0.00

Using the Yc values, the Inter-predictor weight (Int. wt) of each of the causative factors is calculated, and these are used to integrate in weighted multiclass index overlay to prepare the Landslide Susceptibility Score map.

Table 4.1.1b: Inter predictor weights for LOFS

Causative factor	Minimum Yc	Maximum Yc	Absolute difference (Abs diff)	Inter predictor weight (Int. wt)
Slope	-0.26	0.28	0.54	1
Aspect	-0.73	0.18	0.91	2
Elevation	-0.27	0.25	0.52	1
LULC	-0.62	0.73	1.35	3
Lithology	-0.75	0.33	1.08	2
Lineament	-0.78	0.31	1.09	2
Road	-0.41	0.36	0.77	1
Drainage	-0.72	0.48	1.20	2
				Total= 14

The landslide susceptibility score map is prepared using the LOFS of all causative factors and divided by the Total Inter-predictor weights.

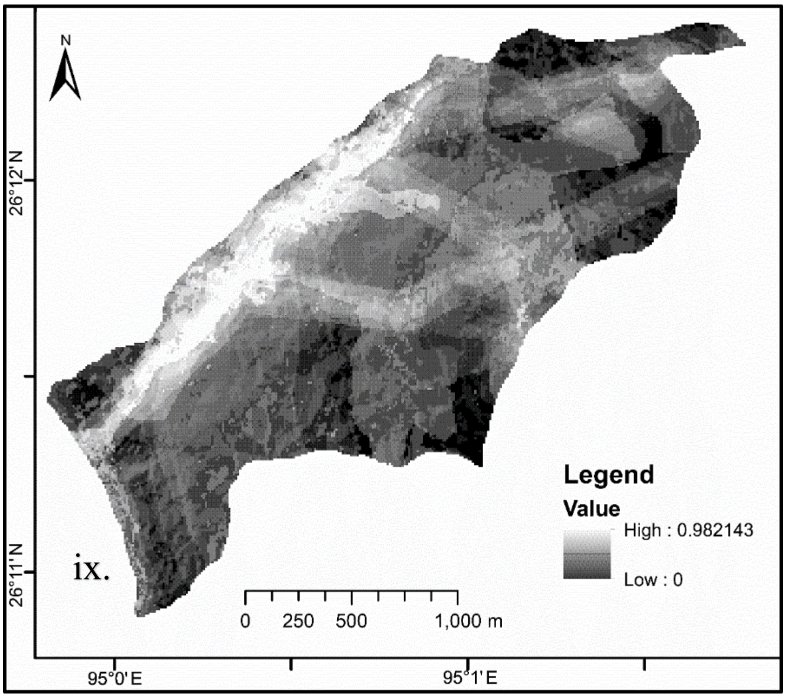


Fig 4.1.1. ix.) Landslide Susceptibility Score map of Noklak town

The success rate curve is prepared to determine the pixel break values for each class of susceptibility.

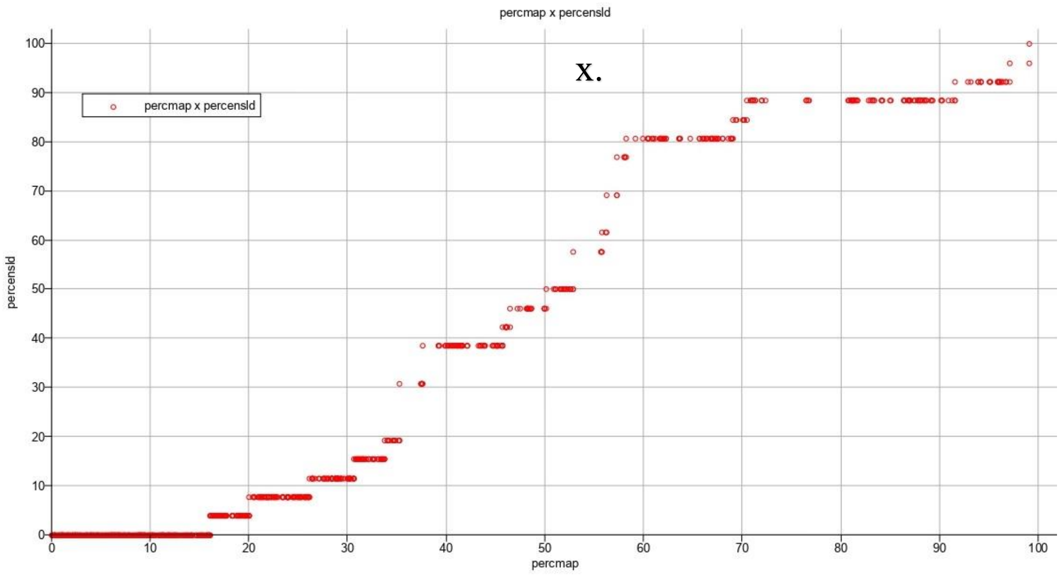


Fig 4.1.1. x.) Success Rate Curve

The study area is classified into high, moderate, and low susceptible areas in the landslide susceptibility map.

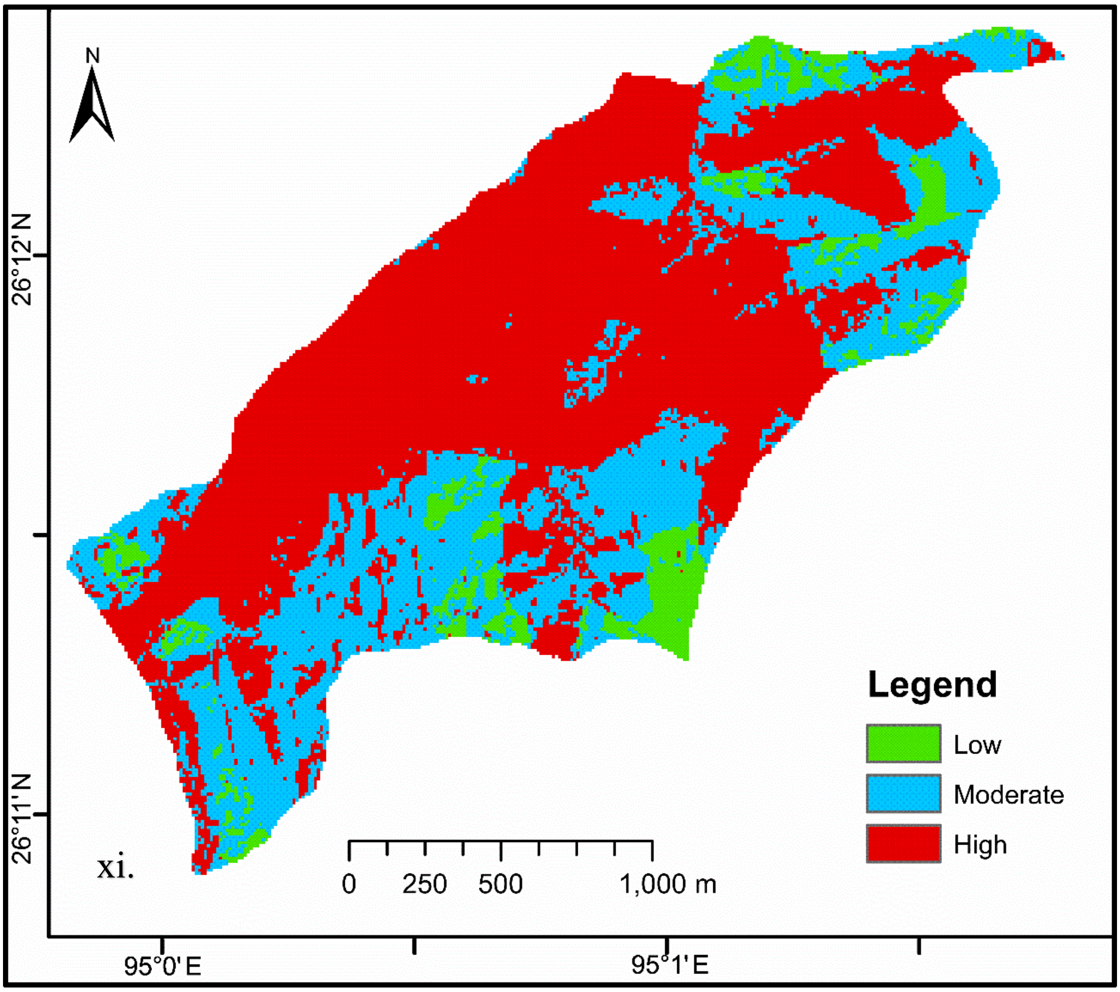


Fig 4.1.1. xi.) LSM of the study area (after Yule 1912)

4.1.2 Information Value method (InV)

The InV maps are prepared by considering the causative factors with the inventory map.

Table 4.1.2: Computed ratios for classes of various data layers based on landslide occurrences:

Slope						
Class	NCPix	Nslpix	Con Prob	Prior Prob	CP/PP	InV
0-10	6235	525	0.084202	0.19155515	0.439571	-0.35697
10-15	6096	668	0.10958	0.19155515	0.572055	-0.24256
15-30	20943	4076	0.194624	0.19155515	1.016018	0.006901
30-45	8673	2670	0.307852	0.19155515	1.607119	0.206048
>45	422	177	0.419431	0.19155515	2.189611	0.340367

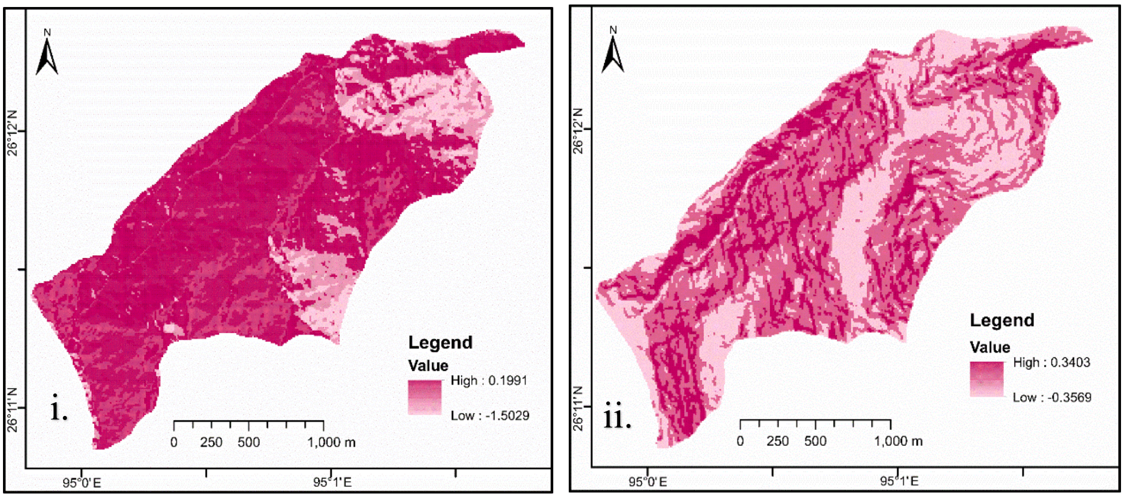
Aspect						
Name	NpixC	Nslpix	Con Prob	Prior Prob	CP/PP	InV
Flat	115	5	0.043478	0.19155515	0.226975	-0.64402
North	835	11	0.013174	0.19155515	0.068772	-1.16259
Northeast	2327	14	0.006016	0.19155515	0.031408	-1.50296
East	4117	126	0.030605	0.19155515	0.15977	-0.7965
Southeast	6572	1579	0.240262	0.19155515	1.254269	0.098391
South	6554	1986	0.303021	0.19155515	1.5819	0.199179
Southwest	6587	785	0.119174	0.19155515	0.62214	-0.20611
West	10576	2502	0.236573	0.19155515	1.235014	0.091672
Northwest	4147	1082	0.260912	0.19155515	1.36207	0.134199
North	539	26	0.048237	0.19155515	0.25182	-0.59891

Elevation						
Name	NpixC	Nslpix	Con Prob	Prior Prob	CP/PP	InV
<900	3293	431	0.130884	0.19155515	0.683269	-0.16541
900-1000	4081	1490	0.365107	0.19155515	1.906013	0.280126
1000-1100	5442	1604	0.294745	0.19155515	1.538693	0.187152
1100-1200	4150	1359	0.32747	0.19155515	1.709533	0.232878
1200-1300	7664	1399	0.182542	0.19155515	0.952946	-0.02093

LULC						
Name	NpixC	Nslpix	Con Prob	Prior Prob	CP/PP	InV
Water body	186	54	0.290323	0.19155515	1.515608	0.180587
Settlement	8537	459	0.053766	0.19155515	0.280681	-0.55179
Barren land	5196	4302	0.827945	0.19155515	4.322226	0.635707
Cultivated land	6197	203	0.032758	0.19155515	0.17101	-0.76698
Forest	21190	3028	0.142898	0.19155515	0.745987	-0.12727
Road	1063	70	0.065851	0.19155515	0.343772	-0.46373

Lithology						
Name	NpixC	Nslpix	Con Prob	Prior Prob	CP/PP	InV
Crumbled shale	12844	738	0.057459	0.19155515	0.299959	-0.52294
Silty shale	3497	753	0.215327	0.19155515	1.124101	0.050806
Weathered shale	19449	5829	0.299707	0.19155515	1.564599	0.194403
Shale with sandstone	2454	774	0.315403	0.19155515	1.646541	0.216573
Soil debris	4125	177	0.005333	0.19155515	0.027842	-1.5553

Lineament						
Distance (km)	NpixC	Nslpix	Con Prob	Prior Prob	CP/PP	InV
50.00	8703	3278	0.376652	0.19155515	1.966284	0.293646
100.00	7415	2371	0.319757	0.19155515	1.66927	0.222527
150.00	6594	1286	0.195026	0.19155515	1.018118	0.007798
200.00	5121	850	0.165983	0.19155515	0.866504	-0.06223
250.00	3061	170	0.055537	0.19155515	0.289929	-0.53771
300.00	2135	55	0.025761	0.19155515	0.134484	-0.87133
500.00	4471	85	0.019011	0.19155515	0.099248	-1.00328
600.00	1958	9	0.004597	0.19155515	0.023996	-1.61986
1000.00	2911	12	0.004122	0.19155515	0.02152	-1.66715



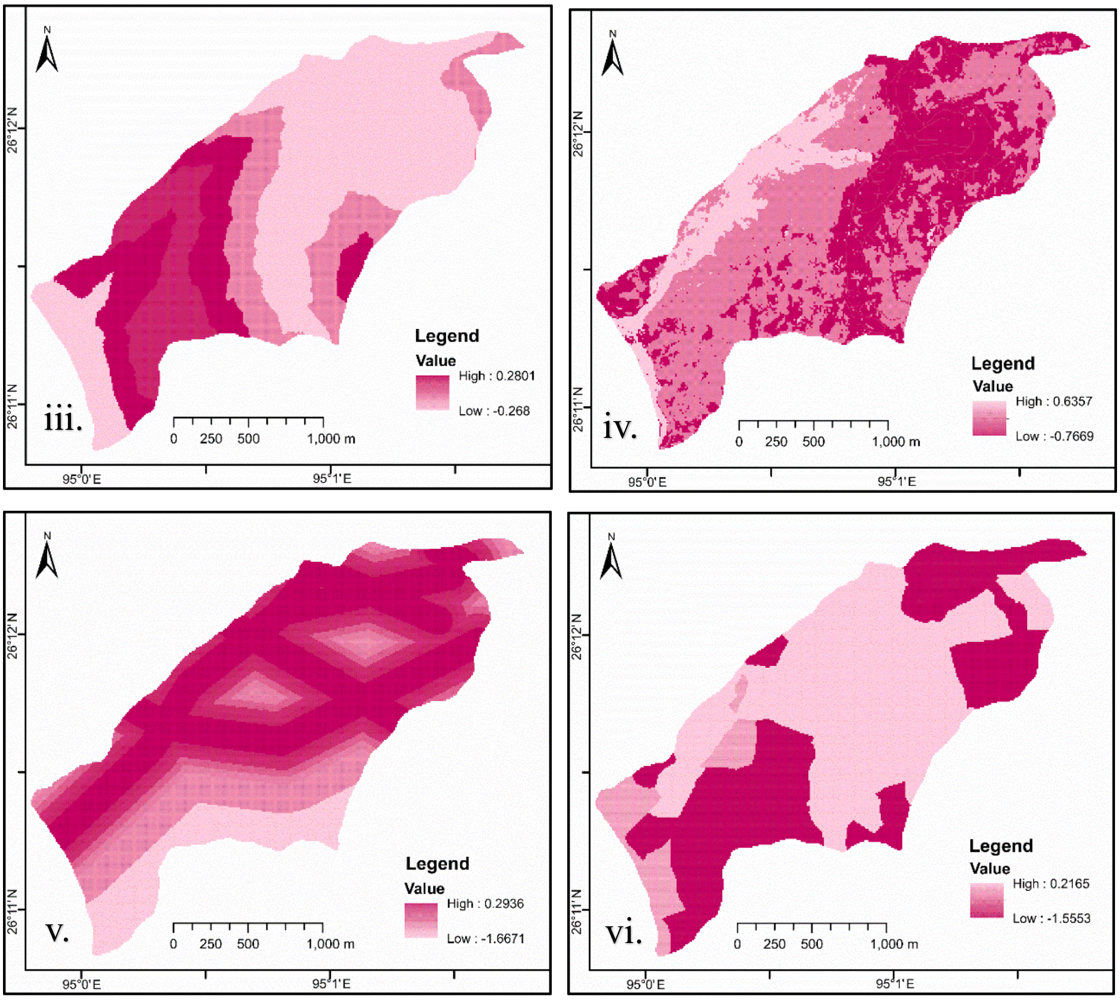


Fig 4.1.2. InV maps of the study area i.) Slope ii.) Aspect iii.) Elevation iv.) Land Use Land Cover v.) Lithology vi.) Lineament

Table 4.1.2: Computed ratios for classes of various data layers based on landslide occurrences:

Road						
Name	NpixC	Nslpix	Con Prob	Prior Prob	CP/PP	InV
10	3133	176	0.056176	0.19155515	0.293264	-0.53274
20	2771	163	0.058824	0.19155515	0.307084	-0.51274
30	2315	121	0.052268	0.19155515	0.27286	-0.56406
40	1837	80	0.043549	0.19155515	0.227346	-0.64331
50	1496	63	0.042112	0.19155515	0.219844	-0.65788
100	4293	263	0.061263	0.19155515	0.319817	-0.4951
500	12001	2770	0.230814	0.19155515	1.204949	0.080969
1200	9879	3949	0.399737	0.19155515	2.086798	0.31948
2000	4644	531	0.114341	0.19155515	0.596909	-0.22409

Drainage						
Distance (km)	NpixC	Nslpix	Con Prob	Prior Prob	CP/PP	InV
10	1578	988	0.626109	0.19155515	3.268557	0.514356
50	5642	2802	0.496632	0.19155515	2.592634	0.413741
100	5919	1919	0.32421	0.19155515	1.692516	0.228533
150	5502	1163	0.211378	0.19155515	1.103482	0.042765
500	20724	1224	0.059062	0.19155515	0.308329	-0.51099
1000	3004	20	0.006658	0.19155515	0.034757	-1.45896

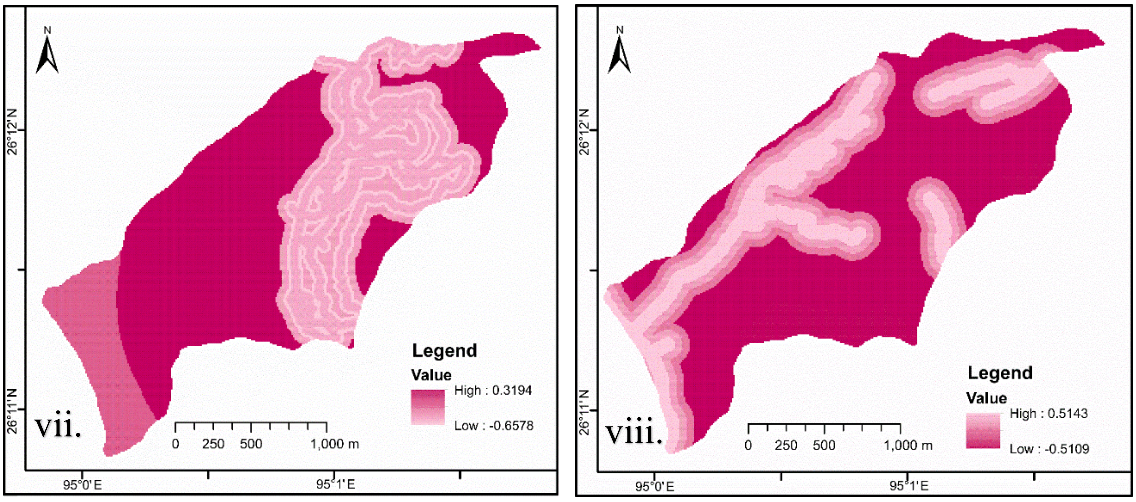


Fig 4.1.2. InV maps of the study area vii.) Road viii.) Drainage

The resulting landslide susceptibility score map, success rate curve and the LSM is given below.

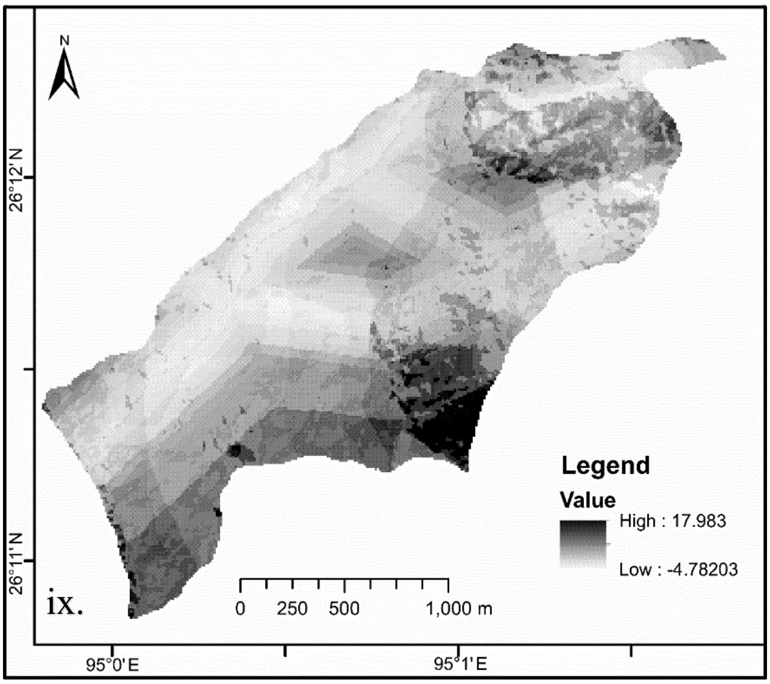


Fig 4.1.2. ix.) Landslide Susceptibility Score map of the study area

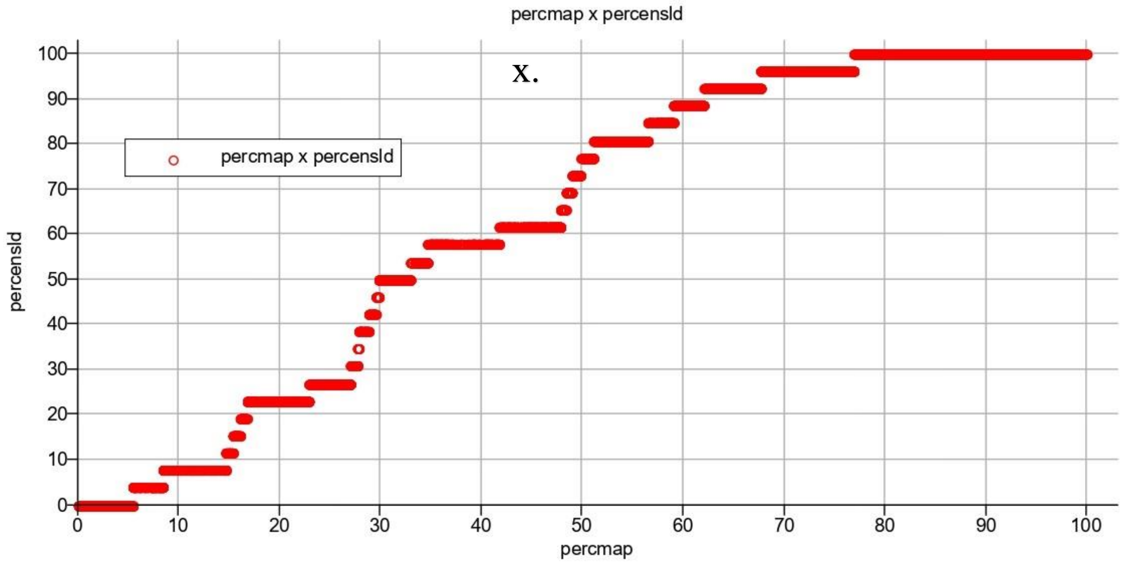


Fig 4.1.2. x.) Success Rate Curve

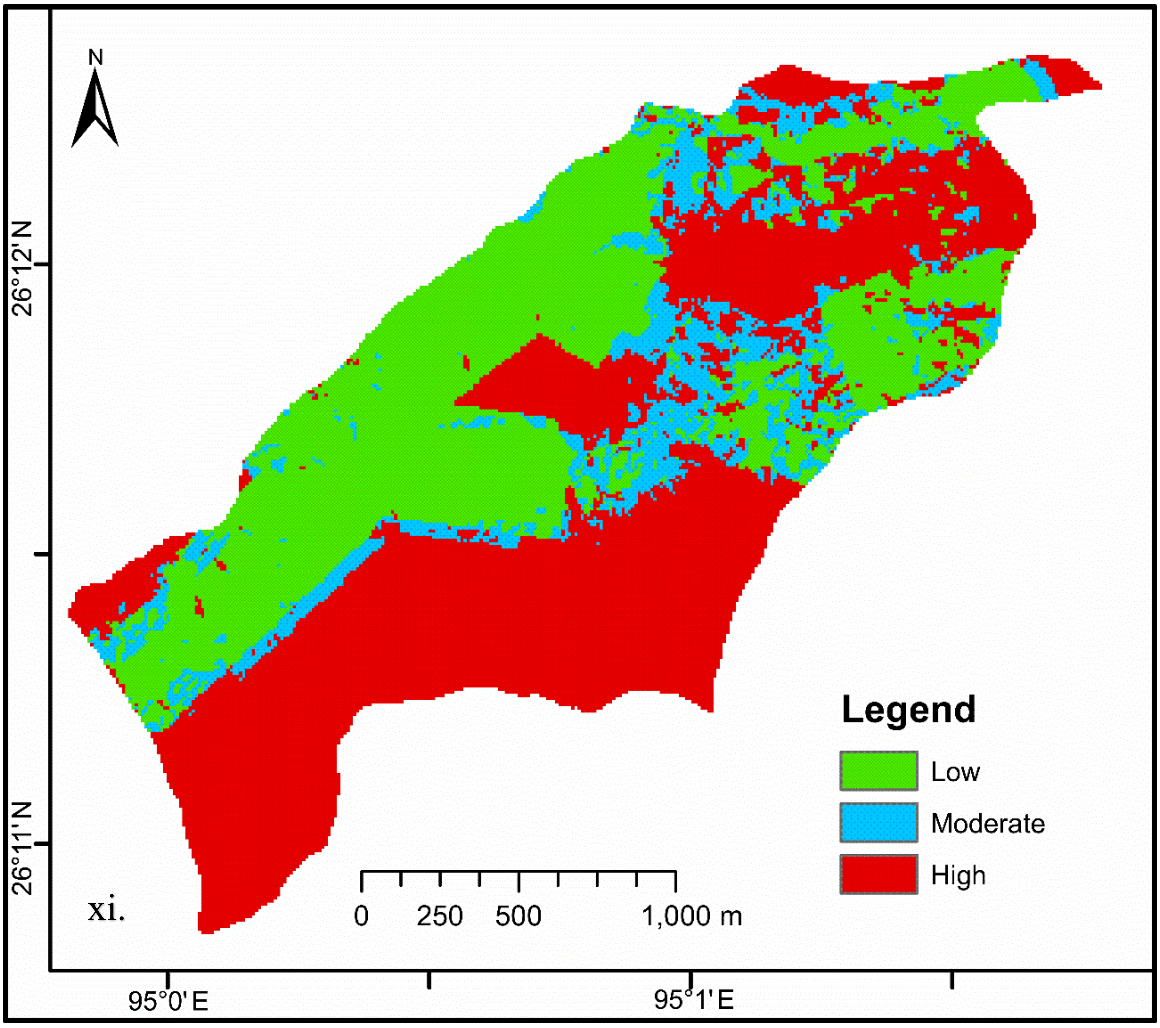


Fig 4.1.2. xi.) LSM of the study area (after Yin & Yan 1988)

4.1.3 Weight of Evidence method (WoE)

The Weight map is built by superimposing each causative factor with the inventory map.

Table 4.1.3: Computed ratios for classes of various data layers based on landslide occurrences:

Slope											
Class	Nmap	Nslide	Nclass	Nslclass	ln for w-	ln for W+	Npix1	Npix2	Npix3	Npix4	C
0-10	42369	8116	6235	525	-1.32272	-1.32435	525	7591	5710	28543	-0.00163
10-15	42369	8116	6096	668	-1.35199	-1.3532	668	7448	5428	28825	-0.00121
15-30	42369	8116	20943	4076	-1.45923	-1.45923	4076	4040	16867	17386	3.96E-06
30-45	42369	8116	8673	2670	-1.646	-1.64606	2670	5446	6003	28250	-6E-05
>45	42369	8116	422	177	-1.45325	-1.45471	177	7939	245	34008	-0.00146

Aspect											
Name	Nmap	Nslide	Nclass	Nslclass	ln for w-	ln for W+	Npix1	Npix2	Npix3	Npix4	C
Flat	42369	8116	115	5	-1.53942	-1.43724	5	8111	110	34143	0.102176
North	42369	8116	835	11	-1.33114	-1.41685	11	8105	824	33429	-0.08571

Northeast	42369	8116	2327	14	-1.30319	-1.37166	14	8102	2313	31940	-0.06847
East	42369	8116	4117	126	-1.32405	-1.33161	126	7990	3991	30262	-0.00756
Southeast	42369	8116	6572	1579	-1.49831	-1.49862	1579	6537	4993	29260	-0.00031
South	42369	8116	6554	1986	-1.57716	-1.57732	1986	6130	4568	29685	-0.00016
South west	42369	8116	6587	785	-1.35497	-1.35597	785	7331	5802	28451	-0.001
West	42369	8116	10576	2502	-1.53942	-1.53955	2502	5614	8074	26179	-0.00014
North west	42369	8116	4147	1082	-1.48868	-1.48917	1082	7034	3065	31188	-0.00049
North	42369	8116	539	26	-1.39226	-1.42796	26	8090	513	33740	-0.0357

Elevation											
Name	Nmap	Nslide	Nclass	Nslclass	ln for w-	ln for W+	Npix1	Npix2	Npix3	Npix4	C
<900	42369	8116	8703	3278	-1.78473	-1.78467	3278	4838	5425	28828	5.13E-05

900-1000	42369	8116	7415	2371	-1.62592	-1.62601	2371	5745	5044	29209	-8.4E-05
1000-1100	42369	8116	6594	1286	-1.44348	-1.44396	1286	6830	5308	28945	-0.00048
1100-1200	42369	8116	5121	850	-1.41645	-1.41729	850	7266	4271	29982	-0.00084
1200-1300	42369	8116	3061	170	-1.36741	-1.37283	170	7946	2891	31362	-0.00543
>1300	42369	8116	2135	55	-1.36655	-1.384	55	8061	2080	32173	-0.01744

LULC											
Name	Nmap	Nslide	Nclass	Nslclass	ln for w-	ln for W+	Npix1	Npix2	Npix3	Npix4	C
Water body	42369	8116	186	54	-1.43195	-1.44266	54	8062	132	34121	-0.01070721
Settlement	42369	8116	8537	459	-1.22713	-1.22909	459	7657	8078	26175	-0.00196011
Barren land	42369	8116	5196	4302	-2.16953	-2.16842	4302	3814	894	33359	0.001117701

Cultivated land	42369	8116	6197	203	-1.26816	-1.27281	203	7913	5994	28259	-0.00465622
Forest	42369	8116	21190	3028	-1.1511	-1.15124	3028	5088	18162	16091	-0.00014076
Road	42369	8116	1063	70	-1.406	-1.41909	70	8046	993	33260	-0.01308388

Lithology											
Name	Nmap	Nslide	Nclass	Nslclass	ln for w-	ln for W+	Npix1	Npix2	Npix3	Npix4	C
Crumbled shale	42369	8116	12844	738	-1.09793	-1.09911	738	7378	12106	22147	-0.00118
Silty shale	42369	8116	3497	753	-1.45284	-1.4537	753	7363	2744	31509	-0.00086
Weathered shale	42369	8116	19449	5829	-2.19955	-2.19926	5829	2287	13620	20633	0.000291
Shale with sandstone	42369	8116	2454	774	-1.48918	-1.48977	774	7342	1680	32573	-0.00059
Soil debris	42369	8116	4125	22	-1.27085	-1.31497	22	8094	4103	30150	-0.04412

Lineament											
Distance (km)	Nmap	Nslide	Nclass	Nslclass	ln for w-	ln for W+	Npix1	Npix2	Npix3	Npix4	C
50.00	42369	8116	8703	3278	-1.78473	-1.78467	3278	4838	5425	28828	5.13E-05
100.00	42369	8116	7415	2371	-1.62592	-1.62601	2371	5745	5044	29209	-8.4E-05
150.00	42369	8116	6594	1286	-1.44348	-1.44396	1286	6830	5308	28945	-0.00048
200.00	42369	8116	5121	850	-1.41645	-1.41729	850	7266	4271	29982	-0.00084
250.00	42369	8116	3061	170	-1.36741	-1.37283	170	7946	2891	31362	-0.00543
300.00	42369	8116	2135	55	-1.36655	-1.384	55	8061	2080	32173	-0.01744
500.00	42369	8116	4471	85	-1.30198	-1.31335	85	8031	4386	29867	-0.01138
600.00	42369	8116	1958	9	-1.27762	-1.38237	9	8107	1949	32304	-0.10476
1000.00	42369	8116	2911	12	-1.27329	-1.35289	12	8104	2899	31354	-0.07961

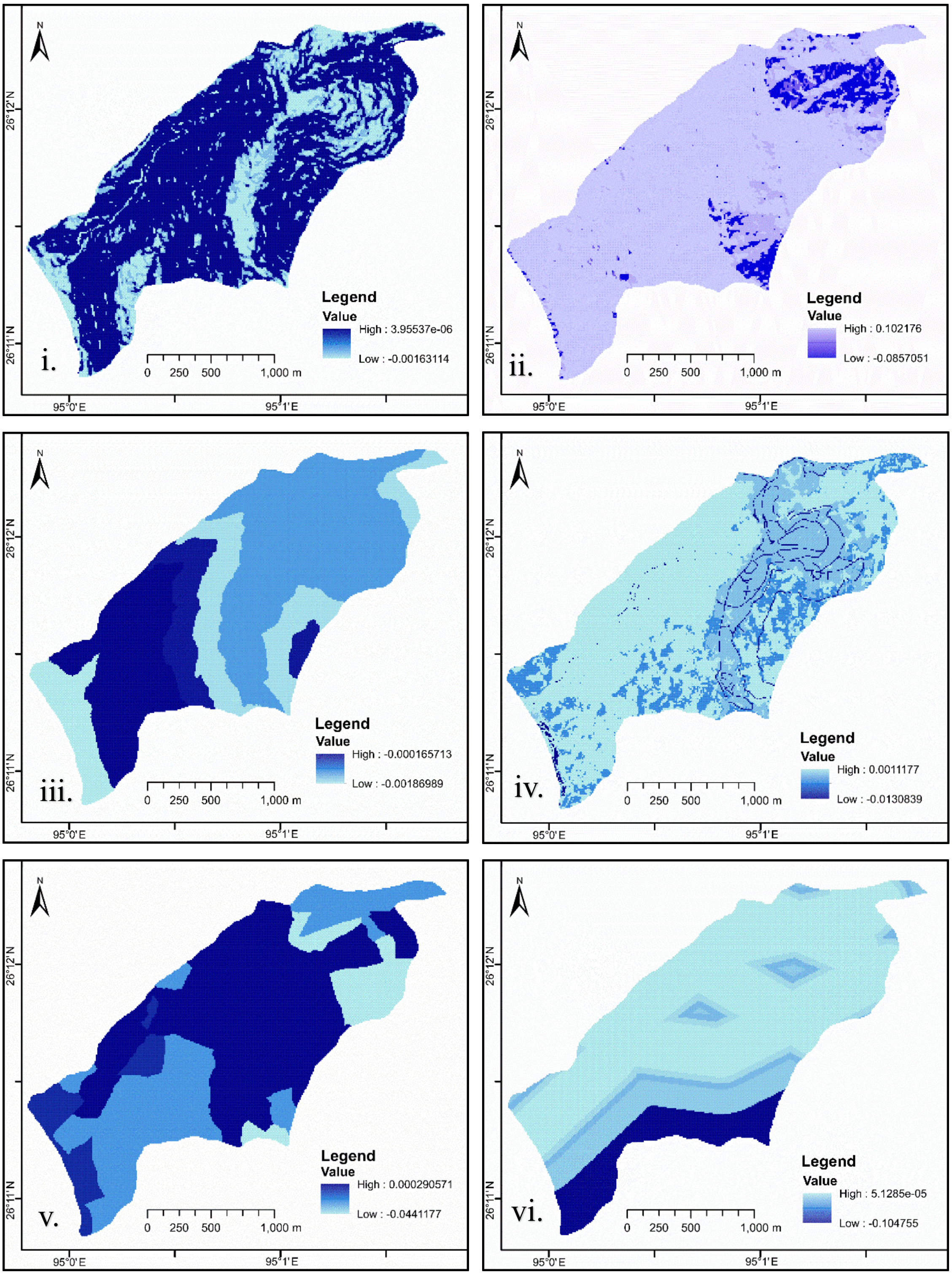


Fig 4.1.3. Weight maps of the study area i.) Slope ii.) Aspect iii.) Elevation iv.) Land Use Land Cover v.) Lithology vi.) Lineament

Table 4.1.3: Computed ratios for classes of various data layers based on landslide occurrences:

Road											
Name	Nmap	Nslide	Nclass	Nslclass	ln for w-	ln for W+	Npix1	Npix2	Npix3	Npix4	C
10	42369	8116	3133	176	-1.366249404	-1.37148	176	7940	2957	31296	-0.00523363
20	42369	8116	2771	163	-1.375298077	-1.38094	163	7953	2608	31645	-0.005638734
30	42369	8116	2315	121	-1.380986794	-1.38867	121	7995	2194	32059	-0.007680936
40	42369	8116	1837	80	-1.385332028	-1.39709	80	8036	1757	32496	-0.01175987
50	42369	8116	1496	63	-1.389942629	-1.4049	63	8053	1433	32820	-0.014957063
100	42369	8116	4293	263	-1.344160637	-1.34761	263	7853	4030	30223	-0.003452718
500	42369	8116	12001	2770	-1.543154199	-1.54326	2770	5346	9231	25022	-0.000105547
1200	42369	8116	9879	3949	-1.916393266	-1.91627	3949	4167	5930	28323	0.000120069
2000	42369	8116	4644	531	-1.378042214	-1.37958	531	7585	4113	30140	-0.001539714

Drainage											
Distance (km)	Nmap	Nslide	Nclass	Nslclass	W-	W+	Npix1	Npix2	Npix3	Npix4	C
10	42369	8116	1578	988	-1.55305	-1.55226	988	7128	590	33663	0.000792
50	42369	8116	5642	2802	-1.77687	-1.77672	2802	5314	2840	31413	0.000152
100	42369	8116	5919	1919	-1.58526	-1.5854	1919	6197	4000	30253	-0.00014
150	42369	8116	5502	1163	-1.45852	-1.45904	1163	6953	4339	29914	-0.00052
500	42369	8116	20724	1224	-0.76032	-0.76101	1224	6892	19500	14753	-0.00069
1000	42369	8116	3004	20	-1.3028	-1.35117	20	8096	2984	31269	-0.04836

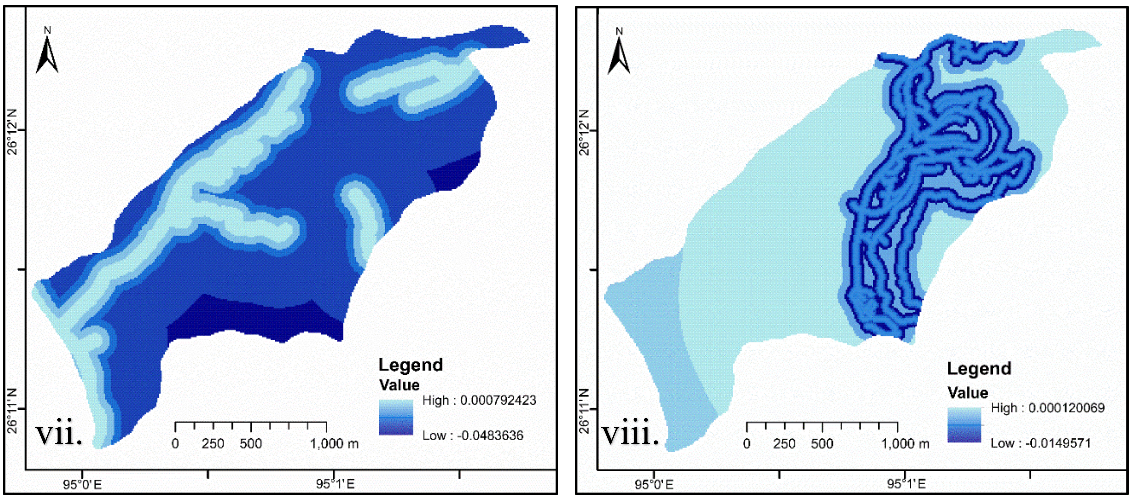


Fig 4.1.3. Weight maps of the study area vii.) Road viii.) Drainage

The resulting landslide susceptibility score map, success rate curve and the LSM is given below.

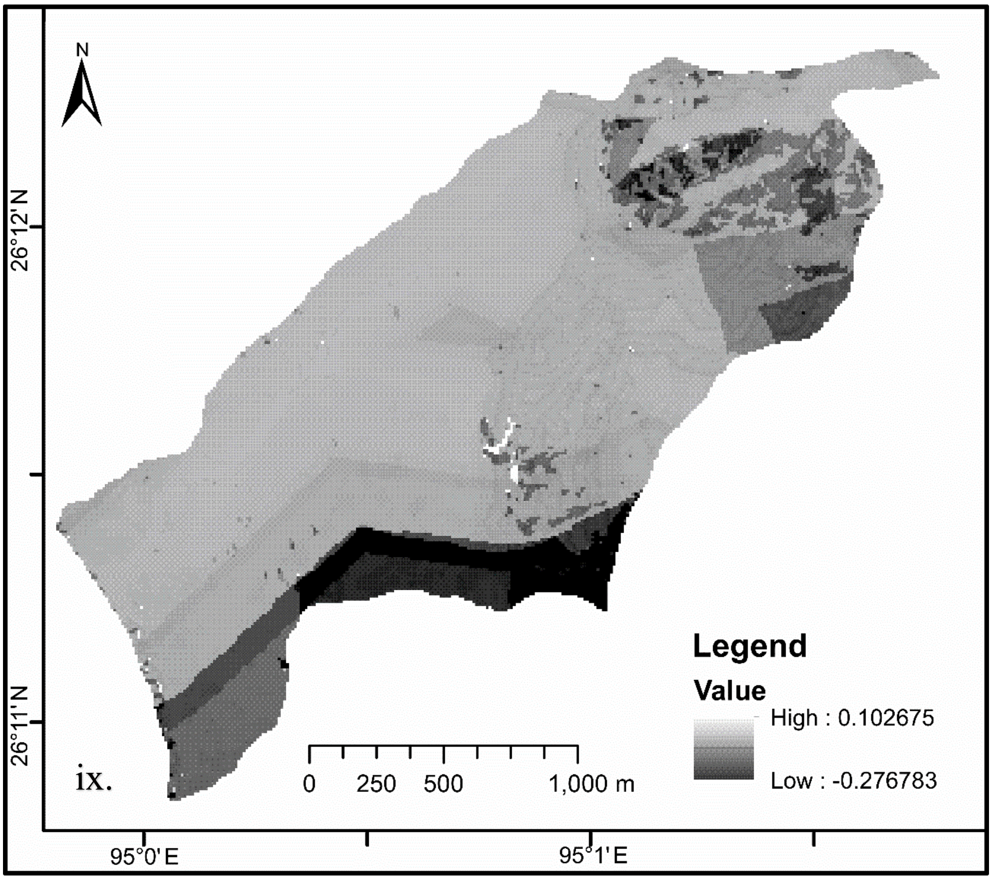


Fig 4.1.3. ix.) Landslide susceptibility score map of the study area

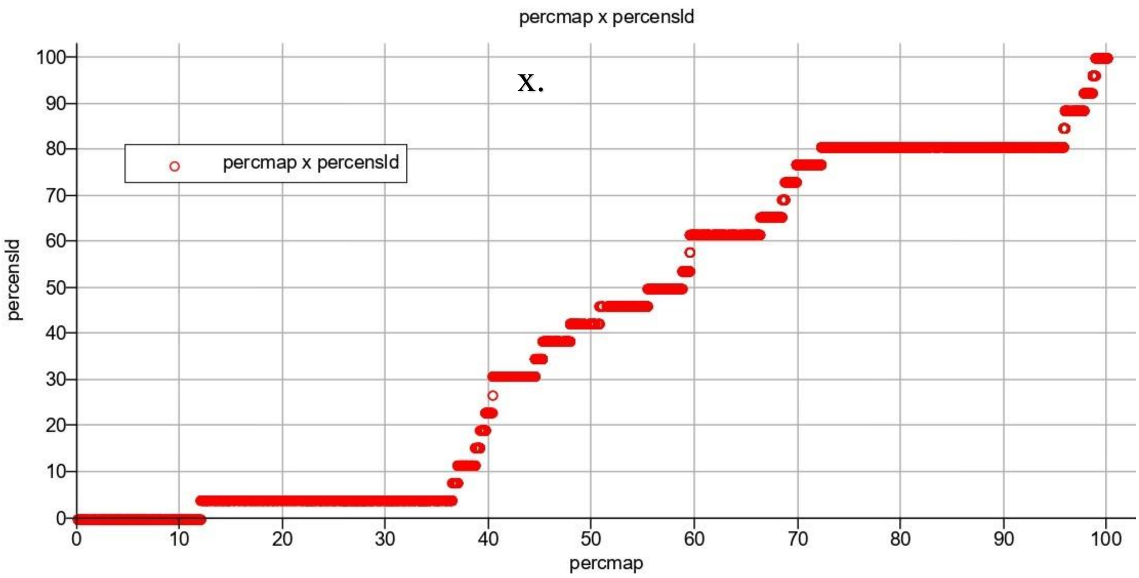


Fig 4.1.3. x.) Success rate curve

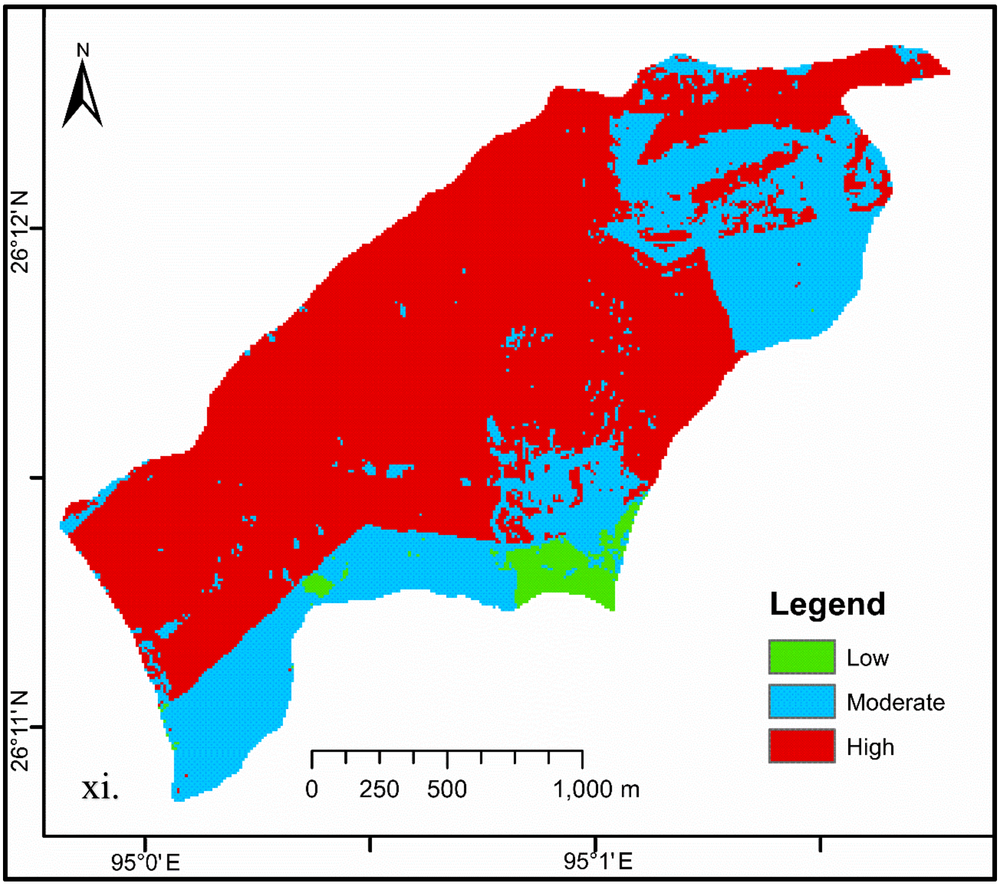


Fig 4.1.3. xi.) LSM of the study area using WoE method

4.1.4 Validation of Landslide Susceptibility map

The 3 LSMs are validated using the Area Under Curve analysis.

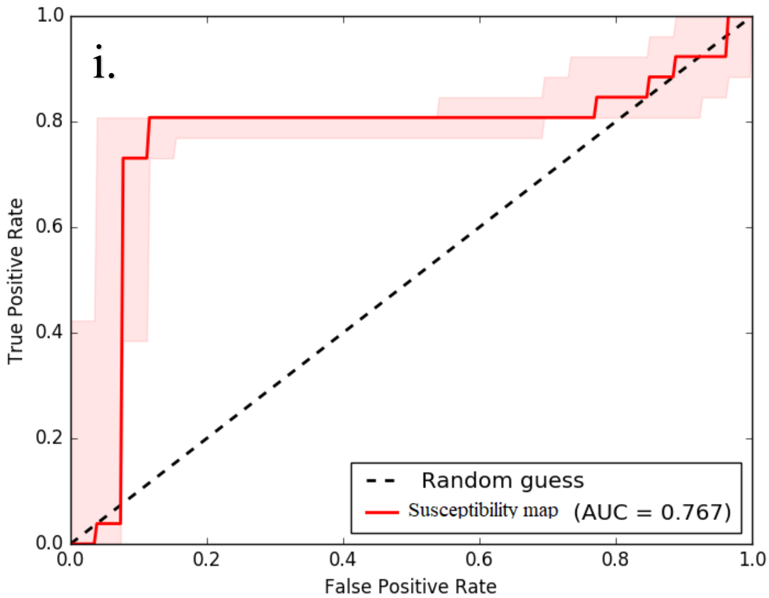


Fig 4.1.4. Graphs depicting ROC and Area under curve i.) Yule coefficient method

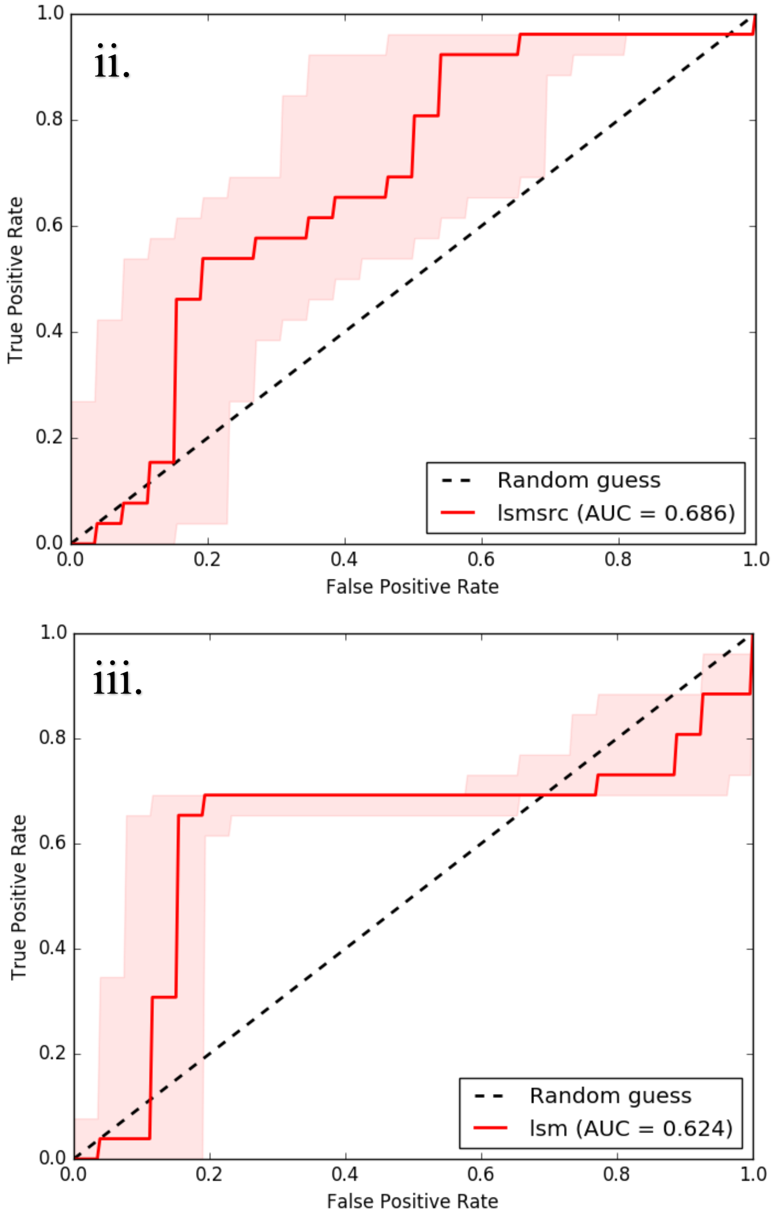


Fig 4.1.4. Graphs depicting ROC and Area under curve ii.) Information value method iii.) Weight of Evidence method

The LSM prepared by the Yule Coefficient method with 77% is found to possess the highest accuracy, and hence it is used for the assessment of the Spatial association and the landslide risk evaluation (Table 4.2)

Table 4.1.4: Comparative table showing AUC percentage for the three methods

	Methods		
Susceptibility class	Yule Coefficient	Information Value	Weight of Evidence
High	75.95%	49.29%	68.57%
Moderate	16.43%	12.62%	29.05%
Low	7.62%	38.09%	2.38%
	AUC=77%	AUC=69%	AUC=62%

4.1.5 Spatial association between the various causative factors and landslide occurrence:

Spatial association between slope and landslides

Slope gradients in the study area vary between 0°- 65°. They have been classified into five categories, which range from 0°-10°, >10°-15°, >15°-30°, >30°-45°, and >45°. It is noted that the majority of the study area has slope inclinations between 15°-30° and bears a positive correlation where the maximum landslide occurs (50.22%). Yc values for gentle slopes (0°-15°) indicate a negative correlation (-0.4).

Spatial association between aspect and landslides

The slope aspect in the study area has been categorized under nine directional classes: flat (0.06%), north (0.46%), northeast (0.17%), east (1.55%), southeast (19.45%), south (24.47%), southwest (9.67%), west (30.83%), and northwest (13.33%). 30.83% lies in the west, and 24.47% in south-facing slopes, account for the bulk of the landslide occurrences. The south, southeast, west, and northwest-facing slopes with Yc values of 0.18, 0.09, 0.09, and 0.11 respectively, indicate a certain degree of positive association with landslides.

Spatial association between elevation and landslides

Yc values for the elevation range from -0.27 to 0.25. A negative correlation is observed at elevations <900 m, 1200-1300, and >1300 m, while a positive correlation is observed between elevations 900-1200 m.

Spatial association between land use/land cover and landslides

The area is categorized under six classes, viz., water body (0.47%), settlement (20.52%), barren land (12.26%), cultivated land (14.45%), forest (50%), and road (2.12%). The occurrences of landslides are highest in the class barren land (53.01%) with a Yc value of 0.73.

Spatial association between lithology and landslides

45.75% of the study area consists of weathered shale, with the highest rate of landslide incidences (71.82%). Landslide incidences are also observed in other areas, regardless. Poor correlation is noted in crumbled shale and soil debris (Yc = -0.40, -0.75 respectively), while the positive correlation with Yc values of 0.33, 0.18, and 0.04 is seen for weathered shale and shale with sandstone and silty shale.

Spatial association between proximity to lineament and landslides

About 40.39% of the landslides are concentrated within a buffer zone of 50 m, followed by 29.21% in a buffer of 100 m from the lineaments. The frequency of landslides decreases with increasing distance from the lineaments. Positive Yc values of 0.01-0.31 are observed within the 50-150 m buffer zones of the lineaments.

Spatial association between proximity to road and landslides

About 82.79% of the landslide incidences are situated 500-1200 m (Yc = 0.08-0.36) away from the road. Therefore, the correlation between the association of roads and landslides is very poor.

Spatial association between proximity to drainage and landslides

34.52% and 23.64% of the landslides are distributed within 50 m and 100 m buffers from stream channels. The frequency of landslides decreases further away from the drainage lines. The association of landslides with drainage is relatively high, between 10-100 m, where Yc values range from 0.2 to 0.5.

The final LSM categorizes the study area under three classes, viz., low, moderate, and high landslide susceptibility. The high susceptible zones comprise 75.95% of the study area, 16.43% under moderate, and 7.62% in low susceptible zones.

4.1.6 Validation of Landslide Susceptibility map

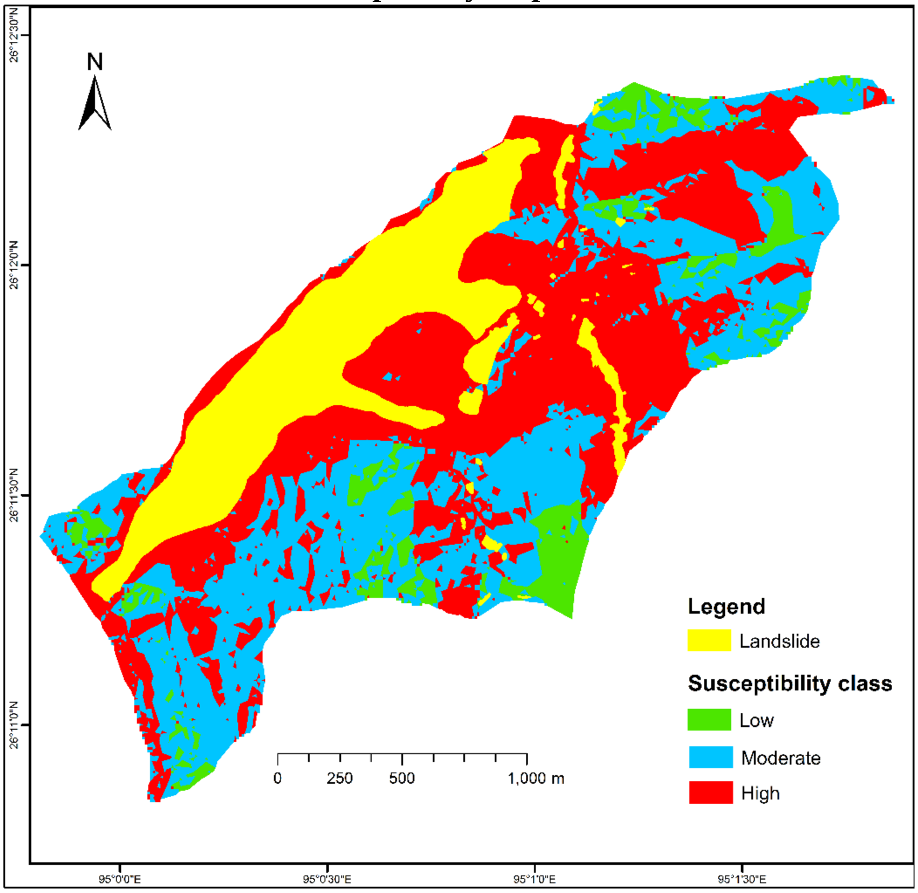


Fig 4.1.6. Validation of landslide incidences

The LSM was overlain by the 26 landslides mapped in the study area to validate results (Fig. 4.1.6). Here, 98.9%, that is, 0.81 km^2 of the landslide area of the total of 0.82 km^2 falls in the high susceptibility class (Table 4.1.6). The larger landslides of the area are responsible for extensive damage to parts of this township. The smaller landslide incidences marked in the moderate and low susceptibility zones are a consequence of human activity, including cutting of weak slopes for various purposes.

Table 4.1.6: Landslide inventory and validation of results with respect to susceptibility classes

Susceptibility class	**No. of landslides**	**Landslide area**		**Susceptible area**	
		(km^2)	*(%)*	*(km^2)*	*(%)*
High	20	0.81	98.9	2.50	75.95
Moderate	4	0.003	0.6	1.43	16.43
Low	2	0.002	0.5	0.31	7.62
Total	**26**	**0.82**	**100**	**4.24**	**100**

4.2 Landslide vulnerability assessment

The elements at risk in the area are identified as buildings, roads, barren land, cultivated land, forest, and water bodies.

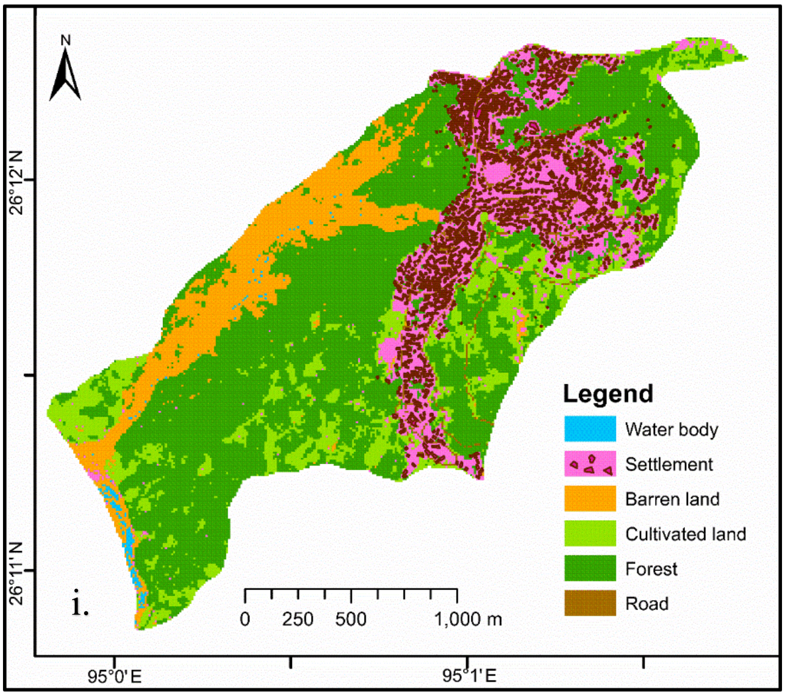


Fig. 4.2. i.). Distribution map of elements at risk

The degree of damage from landslides for each element at risk is used to prepare the landslide vulnerability map

Table 4.2: Degree of damage for elements at risk

Sl no.	Landslide area (in sqkm)	Elements at risk (on a scale of 0 - 1)					
		Settlement	Cultivated Land	Water Body	Forest	Barren Land	Roads
1	0.0112	0.5	0	0	0	0	0.5
2	0.0003	0.5	0	0	0	0	0.5
3	0.0006	0.5	0	0	1	0	0
4	0.0004	0.5	0	0	0.5	0	0.5
5	0.0018	1	0	0	0.5	0	0.5
6	0.0011	0.5	0	0	0.5	1	0.5
7	0.0004	0.5	0	0	0	0	0.5
8	0.0241	0.5	0	0	1	0	0.5
9	0.0077	1	0.5	0	0.5	0	0.5
10	0.0005	0.5	0	0	0	0	0
11	0.0011	0.5	0	0	0.5	0	0.5
12	0.0007	0.5	0.5	0	0.5	0	0.5
13	0.0031	0.5	0	0	0	0	0.5
14	0.0005	0.5	0	0	0	0	0.5
15	0.001	0.5	0.5	0	0.5	0	0.5
16	0.0005	0.5	0.5	0	0.5	0	0.5
17	0.0002	0.5	0	0	1	0	0.5
18	0.0003	0.5	0	0	1	0	0.5
19	0.0002	0.5	0	0	0	0	0.5
20	0.0001	1	0	0	0	0	0.5
21	0.0003	0.5	0	0	0	0	0
22	0.001	0.5	0	0	0.5	0	0.5
23	0.0004	0.5	0	0	0	0	0.5
24	0.0011	1	0	0	0.5	0	1
25	0.728725	0	1	1	1	1	0.5
26	0.0285	0	1	1	1	1	1
Total		14	4	2	11	3	12.5
Average		0.538	0.153	0.076	0.423	0.115	0.48

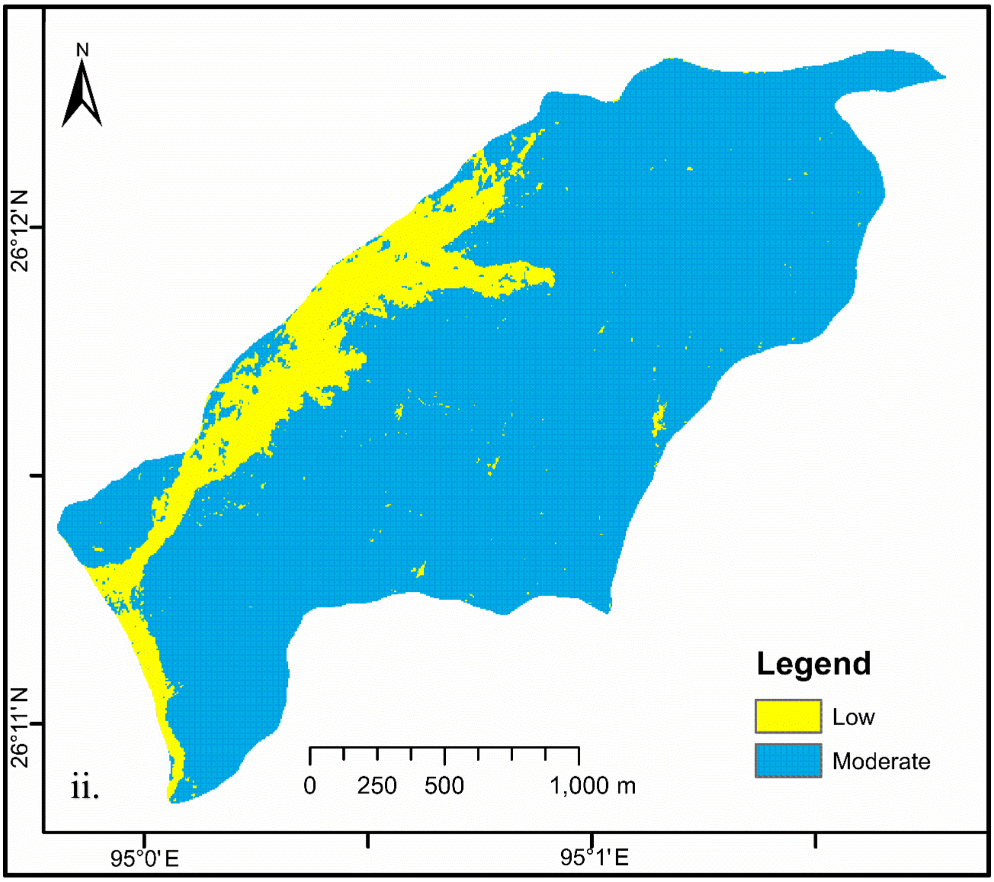


Fig 4.2. ii.) Landslide Vulnerability map

4.3 Landslide Risk assessment

Table 4.3: Percentage exposure for elements at risk

Elements at risk	**Risk class**			**Total**	**Percentage exposure**		
	High	Moderate	Low		High	Moderate	Low
Buildings	1135	756	157	2048	55.42	36.91	7.67
Population	6243	4158	863	11264	55.42	36.91	7.67
Roads (km)	9.16	5.55	1.58	16.29	56.23	34.07	9.70
Cultivated land (sqkm)	0.06	0.30	0.24	0.61	9.84	49.18	39.34
Barren and degraded land (sqkm)	0.03	-	0.49	0.52	5.77	-	94.23
Forest (sqkm)	1.18	0.76	0.17	2.11	55.92	36.02	8.06
Water body (sqkm)	-	-	0.02	0.02	-	-	100

The landslide risk map is finally prepared by overlaying the Vulnerability map over the Landslide susceptibility map that was generated using Yule's Coefficient method.

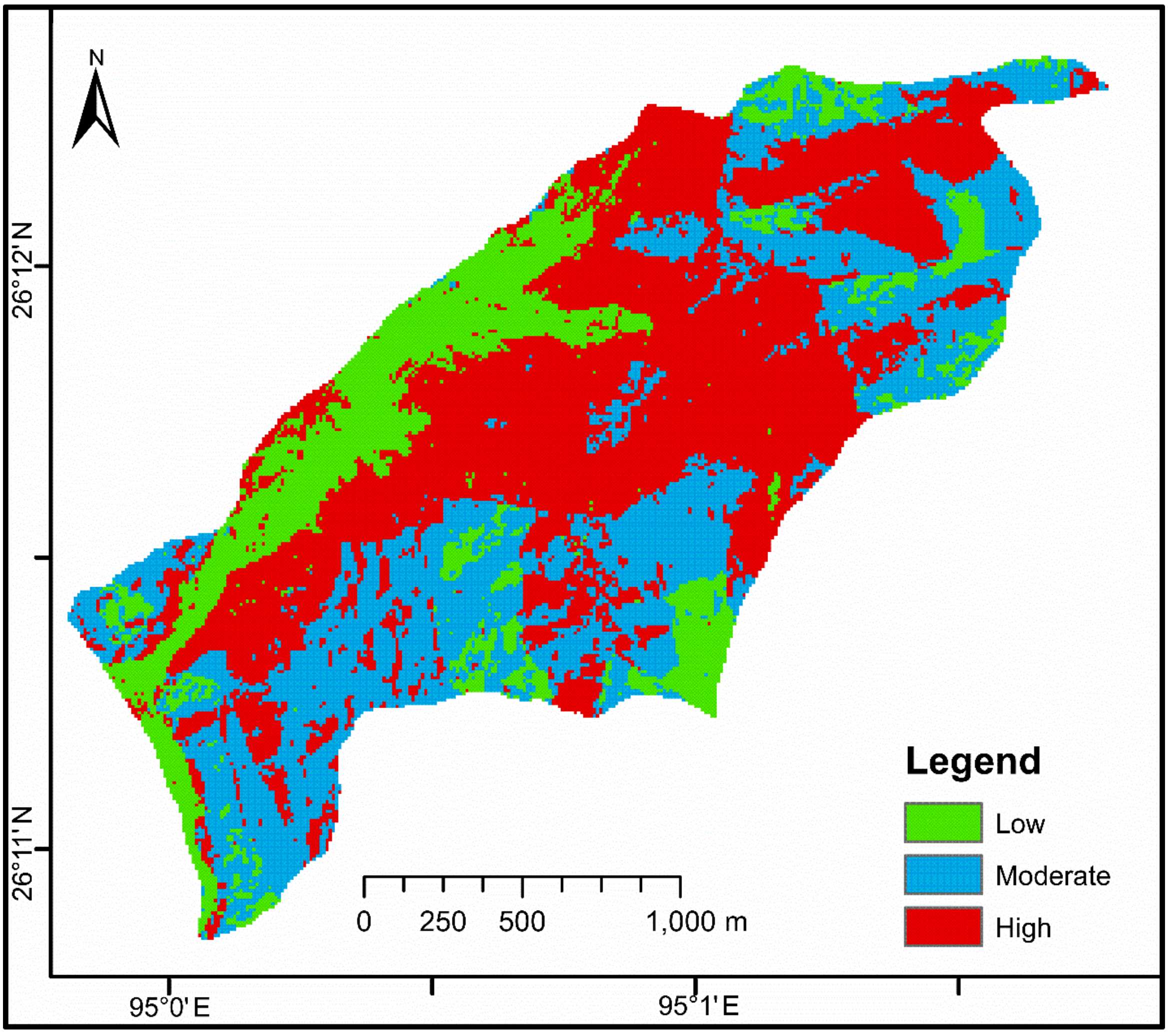


Fig 4.3. Landslide Risk map

CHAPTER 5

DISCUSSION AND CONCLUSION

Landslides are major hazards in mountainous and hilly areas like the state of Nagaland. The complex geomorphic and tectonic setting, climatic conditions, geology, rugged terrain, haphazard and unscientific infrastructural developments are usually some of the reasons attributed to the instabilities.

Noklak town is situated along the ridgelines and slopes in the eastern part of Nagaland. It rests over the Disang Group of rocks. Rock exposures are limited, and the depth of the soil cover ranges between 3-5 meters in thickness. The rocks are exposed mainly along the road sections and landslide areas and consist mostly of dark grey to fawn-coloured splintery shales that are highly jointed, folded, fractured and have undergone various degrees of weathering and possibly minor metamorphism (Fig 5.1). It is a mid-size town that has been accorded the status of a district administrative headquarters only in 2021. It will become the nerve center for the construction of all governmental offices, educational institutions, trade, and other activities that are usually expected of a separate district along with urban sprawl. Against this backdrop, the town and some portions beyond the present built-up areas were delineated for landslide susceptibility, vulnerability, and risk evaluation.

A total of twenty-six (26) landslide-affected areas were initially identified from different parts of the study area. The spatial association of landslides was analyzed to understand the spatial distribution of landslides with the various conditioning factors. Eight landslide controlling factors, viz. slope, aspect, elevation, land use and land cover, lithology, proximity to roads, proximity to lineament, and proximity to drainage, were therefore used to prepare the LSM. Using three different Quantitative Bivariate statistical methods in a GIS platform, separate landslide susceptibility maps for Noklak town were prepared.

All three LSMs prepared were then validated using the Area Under Curve analysis. The LSM prepared by the Yule Coefficient method is found to have the highest confidence with 77% accuracy and therefore utilized for all the later analyses, including the assessment for the Spatial association of factors with landslides and the landslide risk evaluation. The LSM demarcates 75.95% of the total study area in high susceptibility, moderate 16.43%, and 7.62% under the low susceptibility category of landslides. From the spatial association, based on the positive correlation with landslides, the most significant landslide-causing factor in the area is found to be the slope, followed by drainage, lithology, elevation, and lineament.

The results show that the landslides are mostly concentrated between elevations of 900- 1200 m with positive Yc values of 0.17-0.25 in relatively steeper slopes of >15°, having a positive association with landslides with Yc values between 0.01- 0.28. It is generally observed that gently dipping slopes are less prone to instability as compared to steeper slopes (Ram et al., 2020).

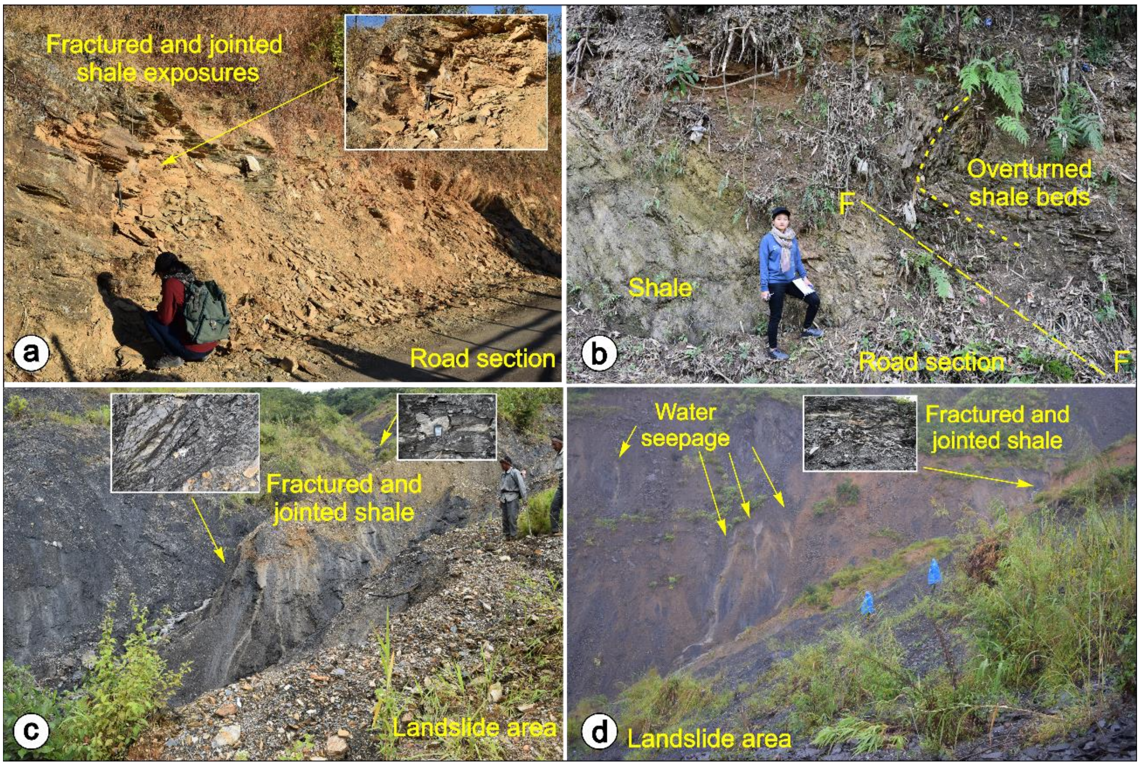


Fig 5.1. a.) Fractured and jointed shale exposures along the road section (b) Local fault (F-F) and overturned fold exposure. (c, d.) Fractured and jointed shale exposures in the landslide area

For any given region, landslides often localize in a specific direction, which may be indirectly related to hydrological processes, such as the direction of rainfall, sunlight, weathering processes, and vegetation cover (Ding et al., 2017). In the study area, the south, southeast, west, and northwest-facing slopes with Yc values of 0.18, 0.09, 0.09, and 0.11, respectively, show a certain degree of positive association with landslides, with the south-facing slope showing the highest Yc value. Several workers have also reported that the south-facing slopes receive more solar insolation, thereby enhancing the weathering process and leading to slope instability (Martha et al., 2011; Sarkar et al., 2013). This may be the reason for the majority of the landslides in the south and westfacing aspect in the present study. Tectonic activity has left its signature in many forms in the region. The subduction of the Indian plate beneath the Burma microplate has led to an NW-SE compression. Lineaments in the form of fractures, joints, faults, etc., greatly reduce the strength of the rocks, which results in a high probability of failure near these features (Kayastha et al., 2012; Sarkar et al., 2013). Satellite imagery shows the study area is also crossed by a number of lineaments, including a major lineament trending NE-SW and cutting across Noklak town (Fig 5.2). And the LSM validated in the field verifies several affected areas of the town falling under high susceptibility zones which lies in and around the lineament trends of the area (Fig 5.3).

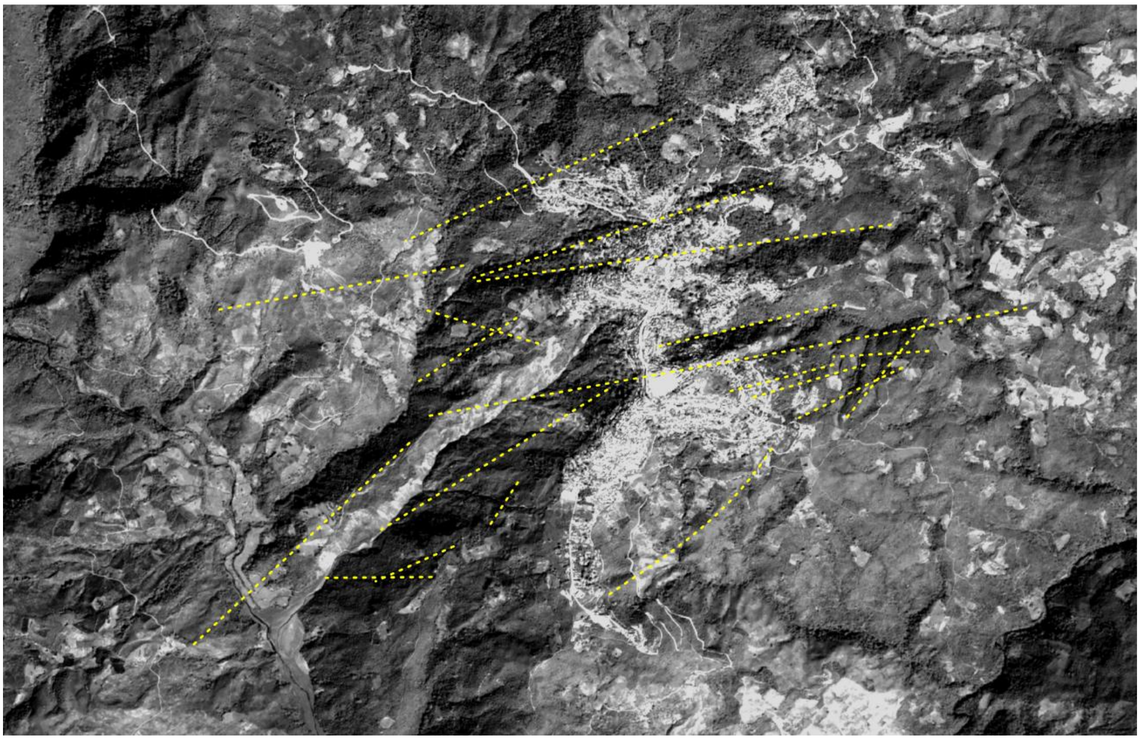


Fig 5.2. Lineament map of the study area and its surroundings

In the present study, the positive values of Yc (0.01 - 0.31) observed within 50m-150m imply the dominant role of lineaments in landslide occurrences. To a large extent, landslides are intimately associated with lithology, as also the drainage conditions and land use/land cover of the area. In this study, a high positive association of landslide is observed in weathered shale, shale with sandstone and silty shale (Yc = 0.33, 0.18, 0.04), barren lands (Yc = 0.73), and water bodies (Yc = 0.14). The shales in many parts of the study area are weak and unstable as they are jointed and crumbled. Shale, when it is weathered to clay, is also expansive by nature and swells and shrinks on wetting and drying. Structures placed upon such rocks are soon damaged by the stresses due to volume change (Mokhtari & Dehghani, 2012) and several houses and roads in and around the town have been damaged. The close proximity drainage lines with Yc values of 0.2 - 0.5 in the study area show a high number of positive correlations and may be regarded as another influential factor causing landslides in the study area. This may be because of the erosivity of the river and since most of the drainage is regarded to be structurally controlled. The lack of proper and sufficient drainage in the study area, there is widespread erosion and infiltration of surface water into the subsurface, particularly during the monsoon. The parameter, road network, plays an insignificant role in the slope instability of the study area, as indicated by the negative Yc values, except between the buffers of 500-1200 m.

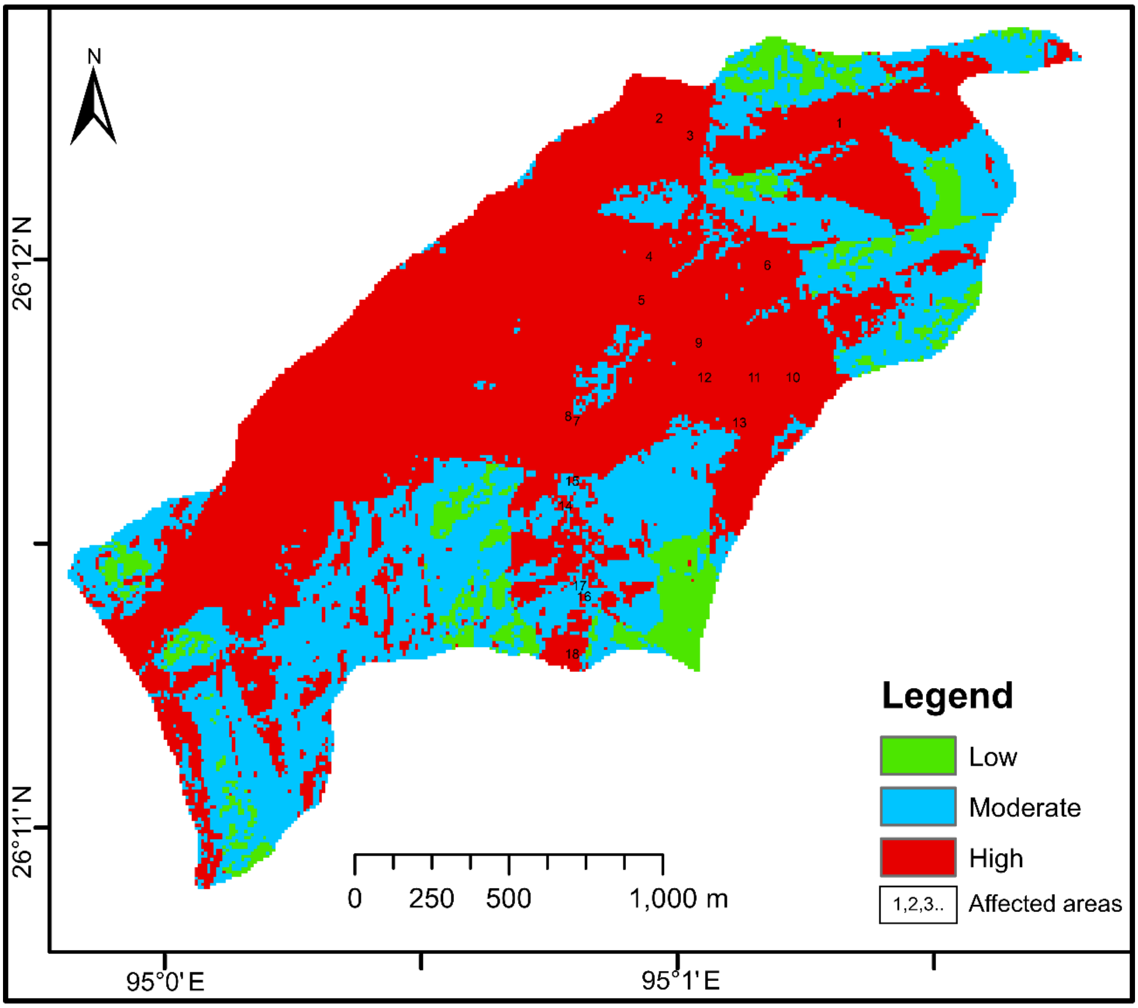


Fig 5.3. LSM with field validation (1 to 18)


1
Road
Subsidence
2
Crown section of the old landslide
3
Tilted shops due to ground subsidence
4
Crown section
of the new landslide
5
Main street
Crown
New landslide zone
6
House tilted due
to ground subsidence


7
Subsidence in a
school compound
(27.8 cm)


8
Fissure(41 cm)
in a school compound


9
Crown sectionof a
new landslide zone


10
Road subsidence


11
Road section
Subsidence along
a road section


12
Crown
Partially damaged road
in a new landslide zone

Limitations:

Few limitations associated with landslide susceptibility studies are observed.

i.) Landslides are localized events controlled by morphological, hydrological, lithological, structural, land-use settings, intensity, duration and extent of the triggering mechanism. Moreover, some of these factors always vary with time due to natural processes. So, every time a landslide occurs, the geological, topographical and hydrological settings of the slope changes, giving rise to slope stability conditions. Hence an area which falls under any classes of susceptibility will not always remain the same, i.e., a low susceptible area may become high susceptible area within a span of years and vice versa under natural conditions.

ii.) Although quantitative methods in Landslide Susceptibility studies are preferable. Till date, no single method has proved to be superior over the other methods in every area and for all types of landslides.

iii.) The notion is that, Landslide Susceptibility maps follow the principle that future landslides are more likely to occur under the same conditions that have triggered past and present slope failures, but it cannot predict when a landslide will occur based on where landslides have occurred in the past.

iv.) Also, another limitation is the difficulty in assessing the frequency and magnitude of the landslides. As such assessments are evaluated by studying historical records or through a multi-temporal analysis of various sets of aerial photographs and such information are quite difficult to obtain.

Scope of the study:

As people move into new areas, it is important to understand their potential exposure to landslide hazards, and how settlements can be planned for land use and infrastructure development in the backdrop of threats from landslides. Geological studies such as Landslide Susceptibility, Vulnerability and Risk Assessment will provide prior knowledge of an area’s slope stability conditions with respect to its susceptibility, the degree of loss to a given element at risk (population, buildings, roads, forests, water bodies, and barren land) resulting from the occurrence of the landslide and the level of risk posed by the it, which will help in good engineering practices and effective enforcement of land-use management regulations, thereby averting damages and reduce the impact by landslides.

Since the study area is still in its nascent stage of development, further slope changes by anthropogenic activities are expected, which will destabilize the slopes. The findings of this study will therefore be of immense help for planners and stakeholders to strategize further activities in the newly established district headquarter.

CHAPTER 6

RECOMMENDATION

Landslides are compulsive and frequent in nature. However, by interventions with appropriate and timely mitigation measures, the impact of landslides can be reduced to some extent. The failures in the past with the usual landslide mitigation approaches in the major slide zone of Noklak town have made it very difficult to come up with a cost-effective and practical recommendation. Nonetheless, the following general measures are recommended for the township:

1. The preparation of a proper and scientific town planning map is a pre-requisite with the expected boost in developmental activities.
2. The Landslide Susceptibility Map generated from this study can be referred to during the preparation of the district headquarter masterplan and for the site selections for all construction activities.
3. Construction of large buildings and other heavy structures should be discouraged in the Highly susceptible areas designated in the LSM, and the Moderately susceptible areas should be developed with caution and after thorough geotechnical investigation only. No developmental activities should be permitted in the landslide zones.
4. Detailed geological, geotechnical, and geophysical investigations, including borehole studies, need to be carried out in and around the township to ascertain the soil and rock characteristics, geological discontinuities, and engineering properties such as bearing capacity, etc.
5. Building codes must be developed by taking into consideration the geological and geotechnical report of the area and should be strictly enforced.
6. Adequate Storm drains and sewerage systems should be designed and installed all over the township in accordance with the slope of the area for proper drainage and to arrest infiltration into the sub-surface. These structures should be properly lined with cement and mortar to avoid leakage and erosion and needs to be maintained regularly to permit the uninterrupted flow of surface water.
7. Waste collection and disposal should be handled efficiently by municipal organizations to avoid clogging the drains due to the improper disposal of waste materials.
8. Rampant cutting of trees has to be stopped, and plantation of trees needs to be encouraged, especially in the landslide zones with plants like vetiver grass, etc. Plantation

with shallow root systems or heavy plant varieties should be discouraged in weak areas to minimize loading and strain on the fragile slope.

9. Roads are very important components of an urban area, and hence new road alignments should be considered according to the geologic and slope conditions of the area, and curbside drains must be constructed along all the road sections.

10. It is observed that the landslides in the study area are caused by many factors. Several pieces of evidence, however, point to the massive neotectonics activity in the region. The study area also falls in the seismic Zone V of India, having the highest risk of damaging earthquakes. It is therefore highly recommended that specialized studies on the role of neo-tectonism on slope instabilities and Active fault mapping must be carried out in the area.

11. Cost-effectiveness is very important when recommending any remedial and mitigation measures. In this connection, to utilize and augment the present infrastructure, it is recommended that the old diversion drain near the Kiamong slide, which was damaged due to a landslide, be repaired and additional provisions made to connect new drains into it. This drain is very vital as it minimizes the amount of water presently flowing into the Kiamong river and would thereby reduce erosion.

12. Several attempts to control the major landslide in Noklak town (Kiamong landslide) by various mitigation measures have failed as the loose debris continue to slide down from the surrounding slopes, covering the structures, while some were washed away by the stream during torrential rain. It is therefore recommended that in the landslide section, huge Hume pipes be placed in the Kiamong river to drain the water out into the Lein river. The pipes will basically serve as a tunnel and as a subsurface drain later when the slope material ultimately slides down and cover them up. Provisions should be made to allow the percolation of water into these pipes so that the surface of the Hume pipes doesn’t act as yet another plane for soil movement. For this, perforations or weep holes may be made at the upper portions of the pipes. Taking into consideration the distance, gradient, and volume of water, check dam structures should be constructed at the floor of the Hume pipes at appropriate distances to reduce the velocity of running water, minimize erosion and ensure the longevity of the structure. The slope that will be formed in the valley after the initial sliding and coverage of the Hume pipes are expected to attain equilibrium, as the slope materials will no longer be removed by toe-river erosion. The resultant slope may then be further vegetated with indigenous plants to bring about further stability in the entire area.

13. The high number of unstable zones in the study area indicates the grave hazard posed by landslides to the population. It is, therefore, important to develop and install Early Warning Systems in strategic locations so as to ensure timely evacuation through monitoring, early prediction, and forecasting of the events.

14. Anthropogenic activities are responsible for most of the landslide incidences in recent years. Public perception and awareness are thus very important not only to reduce their role in the cause of landslides but also to take informed measures to prevent them. It is, therefore, highly recommended that a strong system should be set up to ensure the dissemination of relevant information regarding the causes, responsibilities, risks, and dangers posed by landslides, as well as appropriate penalties for defaulters.

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BIO-DATA OF THE CANDIDATE

I. Publications

1) **Mademshila Jamir**, C. Nokendangba Chang, Imlirenla Jamir, Glenn T. Thong, Temsulemba Walling (2022). "Landslide Susceptibility Mapping of Noklak Town, Nagaland, Northeast India using Bivariate Statistical Method"- Geological Journal, Special Issue Article, vol. 57(12), pp.5250-5264. https://doi.org/10.1002/gj.4595 .

2) **Mademshila Jamir**, C. Nokendangba Chang, Temsulemba Walling, Keneiravinuo (2020). "Kinematic Analysis of Noklak Town Landslide, Nagaland" - Journal Disaster and Development, NIDM, January 2014 - December 2019 issue. ISSN: 0973-6700, vol. 8, No. 1 and 2, pp. 21-36.

II. Papers presented

1) ***"Landslide Susceptibility Mapping of Noklak town, Noklak district, Nagaland"*:** Two days International e-conference on Earth and Environment in Anthropocene (ICEEA 2021) organized by Department of Geology Central University of Karnataka, India jointly with Centre for Environmental Sciences University of Madras, India and Department of Geology University of Madras, India from 29th to 30th 2021.

2) ***"Geotechnical investigation of Kiam landslide, Noklak district, Nagaland"*:** Online International Conference on "Recent Developments in Earth and Environmental Sciences, Natural Resource Management and Climate Change with special focus on Eastern Himalayas" organized by Department of Geology, Sikkim University, Gangtok, from October 8-9, 2020.

III. Workshops and Seminars/Webinars attended

1) Workshop on **Sequence Stratigraphy and Basin Analysis** conducted at the Department of Geology, Nagaland University, Kohima Campus, Meriema from 26th to 30th November, 2018.
2) Workshop on **Geotechnical investigations for landslide studies** organized by DST and Department of Civil Engineering, IIT Guwahati from 28th February to 2nd March, 2019.
3) Training program on **"Landslide Mitigation and detailed Project Report Preparation"** organized by Department of Environmental Studies, North-Eastern Hill University (NEHU), Shillong and sponsored by National Disaster Management Authority (NDMA), New Delhi from 25th to 29th November, 2019.
4) **1st Indo-Japan International** Webinar series on "**Geotechnics for Disaster Mitigation**", organized by National Institute of Technology Karnataka (NITK), Surathkal, India, Indian Geotechnical Society (IGS) Surathkal Chapter, Indian Institute of Technology (IIT) Tirupati, India and Kyushu University, Fukuoka, Japan from 8th to 13th June, 2020.
5) **1st International symposium on Geoethics** organized by International Association Promotion of Geoethics (IAPG) India Chapter in collaboration with

National Institute of Disaster Management (NIDM) India and Amity University Gurugram, Haryana, India on 14th June, 2020.

6) E-lecture on the topic **"Post pandemic challenges of higher education"** organized by Jwala Devi Vidya Mandir PG College, Anand Bagh, Kanpur. Faculty of Commerce. Affiliated to C.S.J.M University, Kanpur on 25th June, 2020.
7) Online Public Lecture on **Monogenetic volcanoes: Origin, Evolution and their control on local paleoenvironment conditions** organized by Department of Geology, K J Somaiya College of Science and Commerce, Somaiya, Vidyavihar on 29th June, 2020.
8) **De glacial origin of barrier reefs along low latitude mixed siliciclastic and carbonate continental shelf edges** organized by Department of Geology, K J Somaiya college of Science and Commerce, Somaiya Vidyavihar on 30th June, 2020.
9) **Recent advances in geotechnical engineering research and practice (RAGeo-RP)** organized by Department of Civil and Environmental Engineering IIT Patna in association with Indian Geotechnical society (IGS) Bihar & Jharkhand chapter; Nepal Geotechnical society (NGS) and Centre for Earthquake Engineering Research (CEER) IIT Patna from 1st to 10th July, 2020.
10) **National Training programme on "Earthquake Risk Mitigation"** organized by NIDM, MHA, GOI & NEHU Shillong from 8th to 10th July, 2020.
11) **International conference on Paleoclimate changes** ICPC-2020 organized by School of Civil Engineering (SCE), Vellore Institute of Technology, Chennai (India) in association with M/S Sense Image Technologies, Chennai from 9th & 10th July, 2020.
12) **ESRI User Conference** India Live 2020 from July 14th to 16th, 2020.
13) **National workshop on Recent advances in Geosciences** conducted by Department of Geosciences, Dr. B.R Ambedkar University, Etcherla, Srikakulam on 31st July, 2020.
14) **Regional level webinar on A talk on- "Communicating: A reflection"** by Prof. T.K. Kharbamon organized by Department of English in collaboration with IQAC Unity College, Dimapur, Nagaland on 4th August, 2020.
15) **3 days training on Climate change Landslides and safe Hill area development** organized by NIDM, MHA, GOI in collaboration with Dr Raghunandan Singh Tolia Uttarakhand academy of Administration, Nainital Uttarakhand from 5th to 7th August, 2020.
16) **Recent earthquakes in Indo-Burmese ranges** organized by Department of Geology, Pachhunga University College, Aizawal Mizoram held on 6th & 7th August, 2020.
17) e-training on **"Fundamentals of Structural Geology"** Exclusively for SC & ST Category conducted by GSITI Hyderabad from 12th to 14th August, 2020.
18) **International level 1-week QGIS training program for the development of GIS platform** conducted by Geotech GIS Training Institute Aurangabad Maharashtra from 12th to 18th August, 2020.
19) Certificate of appreciation awarded for excellent performance in online "**Covid-19 Awareness Programme"** for spreading awareness about the mode of transmission and commitment to discharge the service to the nation, organized by Geotech GIS Training Institute and Consultancy Services, Aurangabad affiliated to Information Technology and Technical Education Council, Delhi on 18th August, 2020.

20) e-training on **"Fundamentals of mapping Techniques in Tertiary Terrain"** (Exclusively for SC& ST Category) conducted by GSI, Regional Training Institute, North Eastern Region, Shillong from 24th to 26th August, 2020.
21) **5 Days National Level webinar on "Landslide & it's Effects-A case study on Kodagu"** organized by Coorg Institute of Technology, Department of Civil Engineering, Kodagu, Karnataka from 8th to 12th September, 2020.
22) e-Training on **"Fundamentals of Palaeontology"** conducted by RTD, ER, GSITI, Kolkata from 10th to 12th September, 2020.
23) e-Training on **"Basics of Geographical Information System and its Applications"** conducted by CGMT Division of GSI Training Institute, Hyderabad from 17th to 19th September, 2020.
24) e-Training on **"Engineering Geology and Landslide Studies"** conducted by RTD, SR, GSITI, Hyderabad from 21st to 26th September, 2020.
25) e-Training on **"14th Course on Application of Geo-informatics for Disaster Management"** under NNRMS Programme of ISRO conducted by Geological Survey of India Training Institute, Hyderabad from 29th September to 12th October, 2020.
26) Online training course on **"Local groundwater related issues and participatory groundwater management"** held at Department of Geology, Nagaland University, Kohima (Nagaland) organized by Department of Water Resources, River Development & Ganga Rejuvenation, Ministry of Jal Shakti, Government of India in collaboration with Central Ground Water Board, North Eastern Region, Guwahati under the aegis of Rajiv Gandhi National Ground Water Training & Research Institute, Raipur on 28th February 2022.

IV. Project JRF (Junior Research Fellow)

"**Landslide risk evaluation of Noklak town, Nagaland**" – Department of Science and Technology (DST) NRDMS Project, New Delhi, India (1st June 2018 to 30th May 2020).