LANDSLIDE SUSCEPTIBILITY MAPPING OF UTTARAKHAND REGION

A DISSERTATION

Submitted in partial fulfilment of the requirements for the award of the degree

Of

MASTER OF TECHNOLOGY

In

EARTHQUAKE ENGINEERING

(With specialization in Seismic vulnerability and Risk Assessment)

By

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CANDIDATE'S DECLARATION

I Gandamala Rakesh, hereby declare that the work carried out in this dissertation entitled, "**LANDSLIDE SUSCEPTIBILITY MAPPING OF UTTARAKHAND REGION**" is being submitted in partial fulfilment of the requirements for the award of degree of **MASTER OF TECHNOLOGY** in Earthquake Engineering with specialization in **SEISMIC VULNERABILITY AND RISK ASSESSMENT** submitted to the Department of Earthquake Engineering, Indian Institute of Technology, Roorkee, is an authentic record of my own work carried out for a period from July 2018 to June 2019 under the supervision of **Dr. JOSODHIR DAS**, Associate Professor, Department of Earthquake Engineering, Indian Institute of Technology Roorkee.

Place: Roorkee **GANDAMALA RAKESH**

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CERTIFICATE

This is to certify that the above statement made by the candidate is correct to the best of my knowledge and belief.

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ABSTRACT

Landslides are transient and instantaneously happening and damaging natural hazard in mountains. However, landslides turn into a disaster mainly due to the immature geology connected with external triggering factors which causing landscape changes and indirect and direct losses. Based on the few reports, more than 15% of the total land area in India is to be affected by landslides. The studies of landslides are rapidly growing because of the urbanization and social economic effects on the terrain regions. The present study area uttarakhand which is covered with 86% hilly regions, which is highly prone to devastating landslides. Landslides cause heavy economic losses and human losses. Hence study to be carried in this mountainous region and identifying the factors controlling the occurrence of the landslides. The (LSZ) Landslide Susceptibility Zonation mapping plays a key role in future urbanization planning to reduce the risk of a potentially catastrophic event. These maps categorized an area according to stability and instability based on parameters which are used in the preparation of Landslide Susceptibility Zonation maps such as slope, aspect, relative relief, drainage, thrusts, and lineaments, lithology, etc. and also triggering factors like seismicity (Earthquake). The (LSZ) Landslide Susceptibility Zonation mapping study is carried for the Uttarakhand region and the process of identification of different zones of landslide susceptibility. A total of 2188 existing historical landslides identified using remote sensing techniques from Google earth pro. The different landslide causative parameters such as slope, aspect, relative relief, drainage, thrusts, and lineaments, lithology, and earthquake are finalized. The qualitative approach of Landslide Susceptibility Zonation mapping (LSZ) is used and the weights, rankings are assigned based on the causative effects for the occurrence of landslides. The data is collected from Google Earth, IMD (Indian Metrological Department), Aster GDEM and previously published maps used to prepare the landslide inventory and prepare thematic layers data integration in an Arc GIS platform. The final Landslide Susceptibility Zonation mapping prepared for the study area separates five different zones based on the susceptibility varying from very low to very high. The results of this dissertation work explain the slope angle, aspect, relative relief, drainage density, thrusts, and lineaments, lithology have the built-in implication of landslide susceptibility and local seismicity affect the landslide occurrence and distribution. These maps can incorporate the future landslide susceptibility in the Uttarakhand region.

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Chapter 1 INTRODUCTION

1.1 General:

The landslides are cataclysmic events. These are momentary and instantly happening natural hazard in hilly and mountain regions. Generally, a landslide occurs when a slope changes from the steady state to an unsteady state. The materials can be moved by falling, sliding, flowing, spreading (U.S. Geological Survey, 1981). Whereas in India about 25% of its geographical area covered under mountainous terrain. And according to a few reports, more than 15 percent of the land area in India is to be influence by landslides. The study of landslides rapidly growing because of the urbanization and social economic effects on the terrain regions. According to the landslides data collected by the IMD (India Meteorological Department) these regions have witnessed some of the devastating landslides in history. For example, in the state of Assam, Guwahati (September 18th, 1948), Darjeeling (October 5th, 1968), in the state of Uttarakhand, Chamoli (March 28th, 1999 triggered after Chamoli earthquake). The most catastrophic among all probably is the recent landslides of very low, low, moderate, high, kedarnath (Uttarakhand region) occurred in the year 2013. Basically, these landslides are triggered due to the multi-day cloud bursting at kedarnath valley and caused flash floods in this region killing about 5000 people and caused property loss worth of Rs. 1000 million.

Where landslide is sudden and powerful catastrophic natural calamities, these can't be completely prevented. However, the intensity and impact may be minimized by the identification and forecasting the problems in advance with the help of disaster mitigation departments, civic-authorities, geoscientists, academic research scholars and practicing engineers.

Sudden occurring natural disasters like landslides and floods are most likely to occur in hilly and mountain areas like the Uttarakhand region. Lesser Himalayas lies in the Uttarakhand region through which three active seismic faults are passing through namely Main Frontal Thrust, Main Central Thrust, and Main Boundary Thrust. According to the (Nath and Sharma, 2018) movements along transverse and longitudinal faults can produce higher magnitude earthquakes and these make slopes more susceptible for triggering of landslides. Chamoli earthquake March 28th, 1999) and Uttarkashi earthquake (October 20th, 1991) are major earthquakes which cause a number of landslides in the Garhwal region of Uttarakhand (Pareek and Sharma, 2008). The earthquakes can not only reactivate the previously occurred landslides but also they create a new one.

According to reports that landslides caused damages in Himalayan regions to cost more than one million US dollars, and also causing deaths about 200 per year, it is up to 30% of such losses worldwide (Naithani, 1999).

In general, the susceptibility of landslide is predicting the probability of spatial phenomenon of slope angle failures. Remote Sensing (RS) can play a crucial role in the generation of landslide inventory map and preparing of thematic layers related to landslide occurrences. Remote Sensing (RS) data undergoes in co- occurrences with other data sources into digital form and analysis in Geographic Information System (GIS), which have made a possibility to generate thematic layers based on different factors contributing for the occurrence of a landslide. These methods provide an ideal opportunity for usage, comparison, validation to produce a landslide susceptibility map.

The landslide susceptibility zonation (LSZ) mapping plays a key role in future urbanization planning to reduce the risk of a potentially catastrophic event. These maps categorized an area according to stability and instability based on parameters which are used in the preparation of landslide susceptibility zonation (LSZ) maps such as slope, aspect, drainage, lithology, relative relief, thrusts, and lineaments, etc. and also the triggering factors like seismicity (earthquake). The landslide susceptibility zonation refers to the classification of a particular area into different zones based on the degree of susceptibility and their abilities of landslide occurrence. Based on their influence on landslides each thematic layer is given weights and ranking.

1.2. Study Area:

Uttarakhand is a state which is covered with 86% hilly regions, where it is highly prone to landslides. Hence it is necessary to do susceptibility zonation for this kind of area. The study area considered for the Landslide Susceptibility Zonation mapping (LSZ) extents about 53483km^2 and the boundary lies in between 29° 04’N and 30°56’N latitudes and 78°04’E and 80°18’E Longitudes (Fig1.1) . The study area includes all types of land-use practice including vegetation, water bodies, barren land, dense forest, etc. It includes districts like Dehradun, Chamoli, Haridwar, Uttarkashi, Pauri Garhwal, Tehri Garhwal, etc.

The present study area which is also belongs to the severe earthquake intensity zone (IV) according to the earthquake resistant design code of India [IS 1893(part-1) 2002] and hence it is prone to earthquake-induced landslides.

A map of the study area had prepared and shown in below figure 1.1,

1.3. Objectives of the study:

- To prepare Landslide inventory data for the study area.
- To prepare various DEM (Digital Elevation Model) derivate of the study area and the analysis of different thematic layers related to the study.
- Preparation of different landslide causing factors such as slope, aspect, drainage, relative relief, thrusts and lineaments, lithology, earthquakes as thematic layers.
- To prepare Landslide Susceptibility Zonation (LSZ) maps.

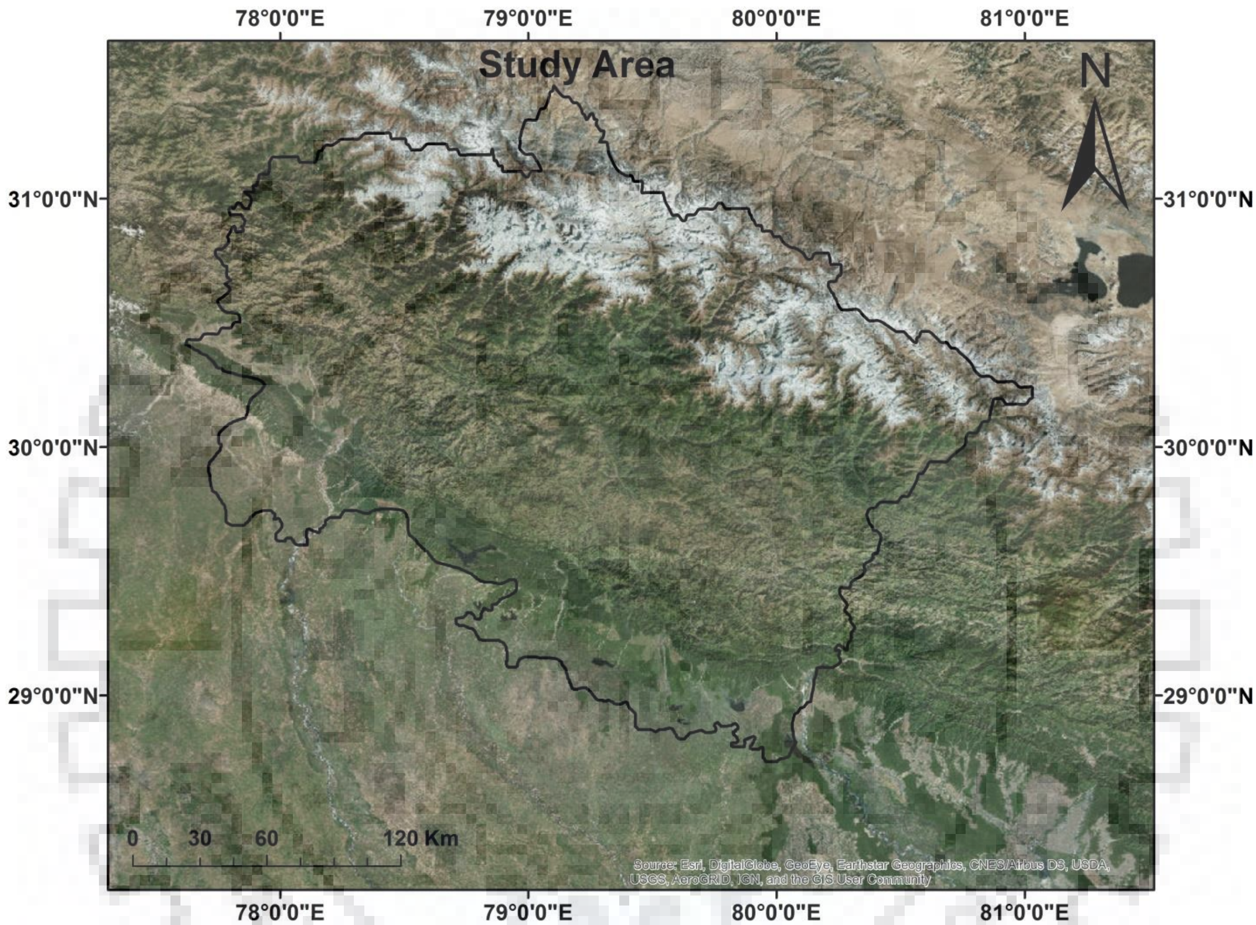


Figure 1.1: Study Area the state of Uttarakhand.

1.4. Scope of the study:

The scope of the present study includes a detailed analysis of different landslide causing factors for the area of interest and identification of landslides in the study area. This study aim is to express the landslide hazard in terms of landslide inventory data collected and maps generated using GIS techniques. Local & regional seismicity plays a key role in geomorphological adjustments which triggers the landslides. Hence the study also considers the influence of local seismicity for Landslide Susceptibility Zonation.

1.5. Data Used:

In this study, the Digital Elevation Model (DEM) is extracted from ASTER GDEM (Global Digital Elevation Model) which is the complete mapping of the earth covering 99% of its surface with a global resolution of 90 meters. The present study area DEM is having resolution of 30 meters Where using GDEM, we can extract such as slope, aspect, relative relief, drainage layers are prepared. Landslide data is collected from Google Earth and inventory data is prepared. India Meteorological Department (IMD) is used to collect Earthquake data.

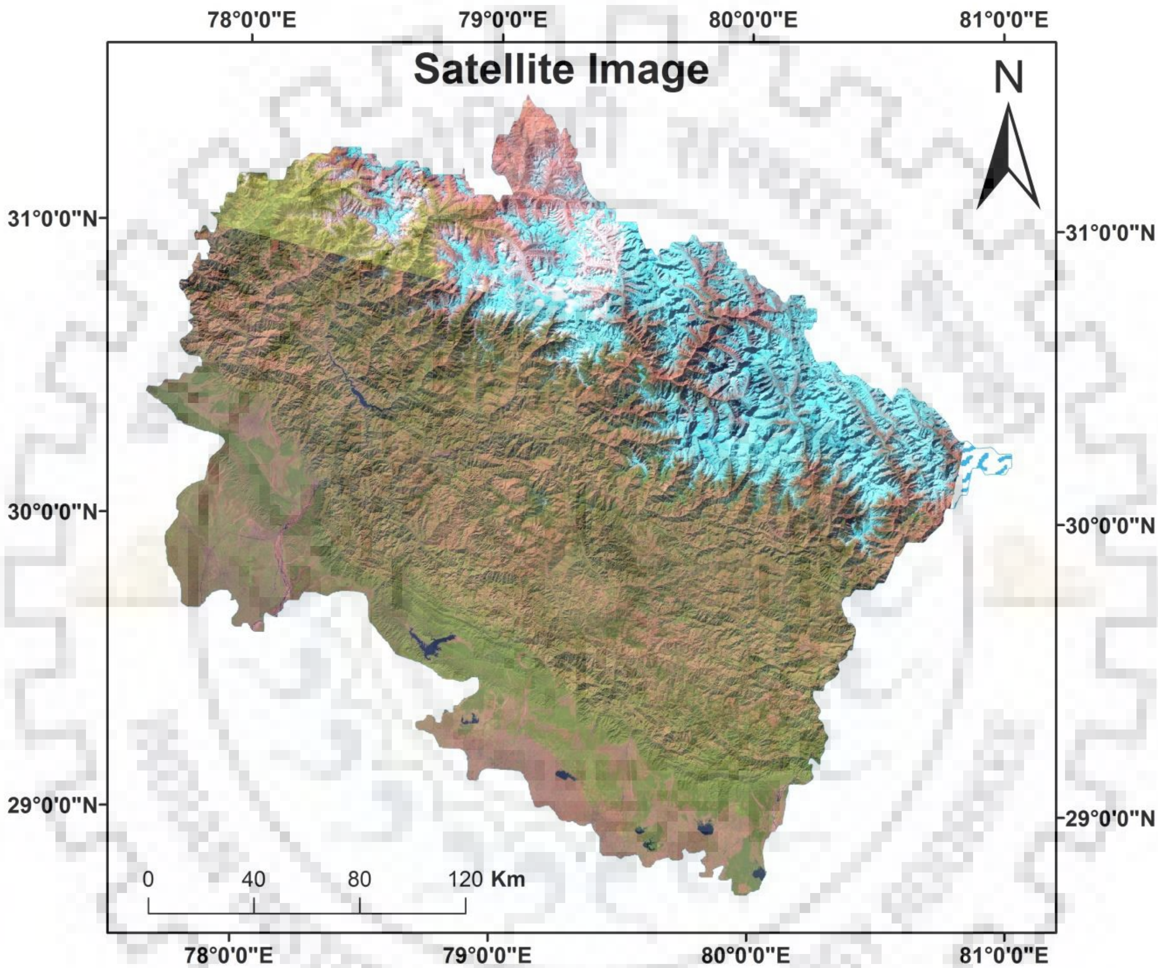


Figure1.2: Satellite image of study area (Uttarakhand).

2.1 General

Landslides are most catastrophic naturally caused risky events in the hilly regions such as Uttarakhand. The study of landslides has drawn worldwide attention due to the pressure of increasing urbanization and awareness of its socio-economic impact in such regions (Aleotti and Chowdhary, 1999). Identification and evaluation of the various landslide causative parameters for analysis of landslide susceptibility. The term Landslide Susceptibility Zonation (LSZ) refers to dividing a particular area into different types of zones based on the degree of their potential of landslide occurrence. For LSZ mapping, data collection is a basic and most important step. Data is generally collected in the form of photographs, maps, field surveys, images, and other information related to the causative factors, which are further analyzed and integrated using different methods for the preparation of LSZ map.

The following chapter assigns with the various aspects of the (LSZ) landslide susceptibility zonation. A detailed study of the literature available for various techniques has also been brought into the limelight.

Varnes and IAEG (1984) define the term “Zonation” as the process of division of land surface into areas and ranking of these areas according to the degree of actual or potential hazard from a landslide or other “mass movements”. Although it is difficult to predict the landslide event in space and time, an area may be divided into near homogeneous domains and ranking is allotted according to degrees of potential hazard due to the mass movements (Varnes 1984). Such maps are called Landslide Hazard Zonation (LHZ) or Landslide Susceptibility Zonation (LSZ) maps. Landslide Susceptibility Mapping (LSZ) is a most important step in landslides risk management and landslide investigation.

Kanungo et al. (1995) explained thLandslide Susceptibility Zonatione method of (LHZ) Landslide Hazard Zonation, which was experimented in Rudraprayag– Srinagar area of the Garhwal Himalaya region.

Table 2.1: Landslide Causative Factors.

Causative factors	
External/triggering factors	**Internal/preparatory factors**
Seismicity	Lithology
	Geomorphology
Toe-erosion by rivers	Land use land cover
	Roads and constructions.
Climate	Structural features
	Hydrogeological conditions

The affecting factors such as, land use, drainage, relative relief, geology, slope angle and all the existing historical landslides contribute to instability. These were studied in relation with frequency of landslide and were numerically weightage allotted based on their influence on landslides. Using this explanation, the present study area was divided into five different zones of instability, and the results were clarified on the field. The map of (LHZ) Landslide Hazard Zonation can be used as a base for the further landslides studies.

Pachauri et al. (1998) mainly focused on producing another key example of Landslide Susceptibility Zonation mapping (LSZ) depending on geomorphological and geological attributes. The data collected from varies available sources such as, Aerial photographs topographic layers, and the data images, which explains about the relation in between the landslides distribution and few geomorphological and geological factors, for example the factors affecting such as the distance from a slope, relief, and active fault. Key parameters like, relief of the region, altitude of the region, slope angle, the distance from the thrusts and lineament and factors of safety are included in this study. Ranking is allotted to the factors arriving at a quantitative method for the estimating landslide susceptibility for each physical causative factor.

Sarkar and Kanungo (2004) presented a key methodology for Landslide Susceptibility Mapping using an integrated remote sensing (RS) and GIS approach. A part of the Darjeeling Himalaya was selected for the implementation of the model. Field data, topographic maps, IRS satellite data, and other informative maps were used as an input to the study. Important factors like terrain, contribution to occurrence of landslides in this region, were the identified and corresponding thematic data layers were generated. These data layers represent the topographical, hydrological conditions, and geological of the terrain. A numerical rating scheme for the factors was developed for spatial data analysis in a GIS. The resulting landslide susceptibility map delineates the area into different zones of four relative susceptibility classes: very low, low moderate, and high. The susceptibility map was validated by correlating the landslide frequencies of different classes. The methodology for landslide susceptibility mapping presented here involves the generation of thematic data layers, development of a suitable numerical rating scheme, spatial data integration, and validation of results. Application of GIS was found extremely useful for thematic data layer generation and for their spatial data analysis, which involved complex operations.

Kanungo et al. (2009) reviewed the advance details in the mapping of landslide susceptibility zoning (LSZ) and examine the suitability about various varieties of approaches for landslide hazard assessment. The review on (LSZ) landslide susceptibility zoning mapping, explains mainly about the two groups of approaches: quantitative approaches and qualitative for Susceptibility mapping. The quantitative approach method became popular for previous decade based on the advancements in the developments of remote sensing (RS) and GIS technologies. Some distribution-free approaches based on fuzzy set and ANN based (Artificial Neural Network) approaches have been attempted to evaluate the landslide susceptibility in the recent years. The fuzzy set based method approach addresses the determination of ratings of the categories only. In most of the ANN (Artificial Neural Network) black box approaches for landslide susceptibility zoning mapping (LSZ), single neural network architecture has been attempted.

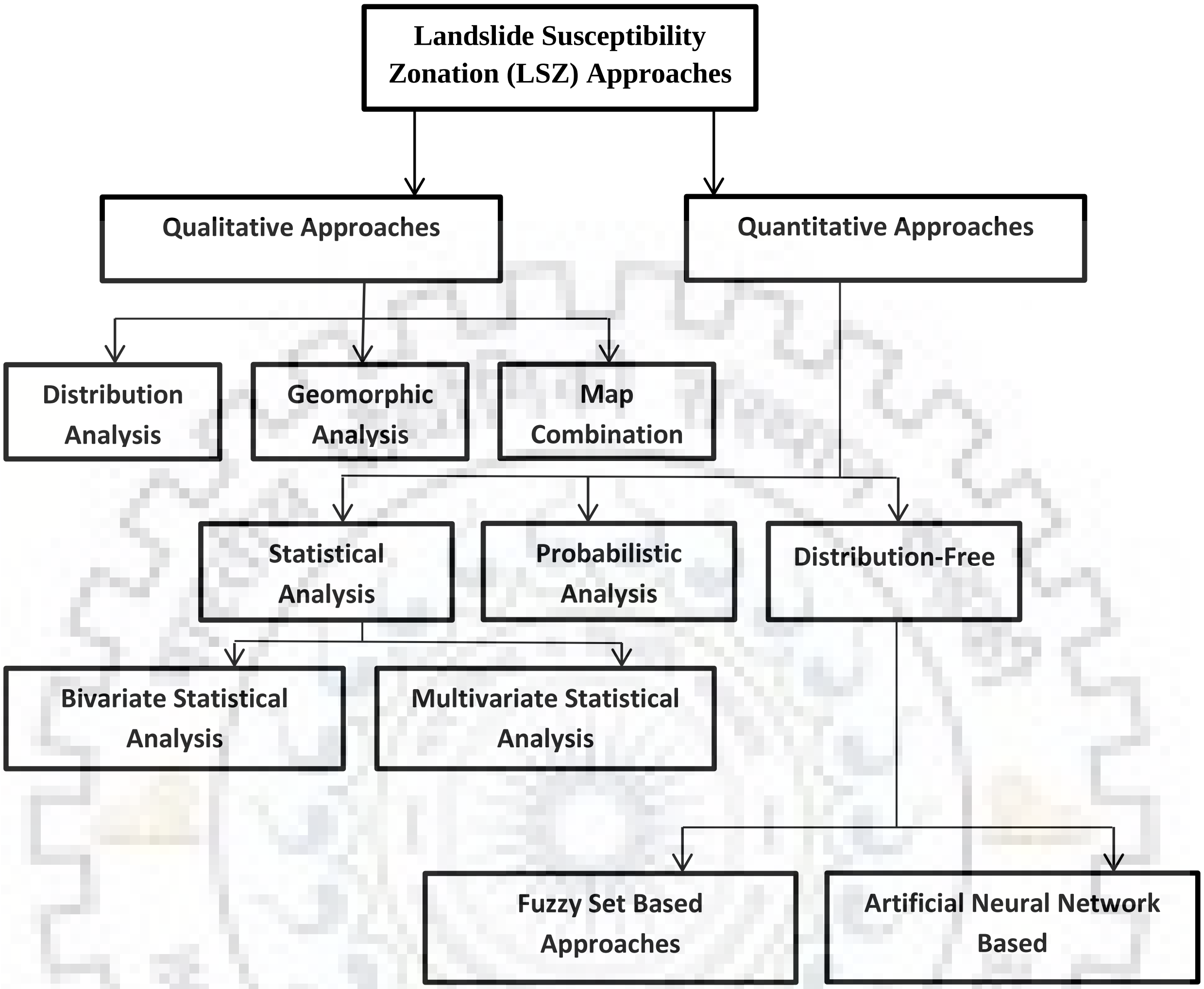


Figure2.1: Different approaches for Landslide Susceptibility Zoning (LSZ) mapping and their classification. (Source: Kanungo et.al., 2009)

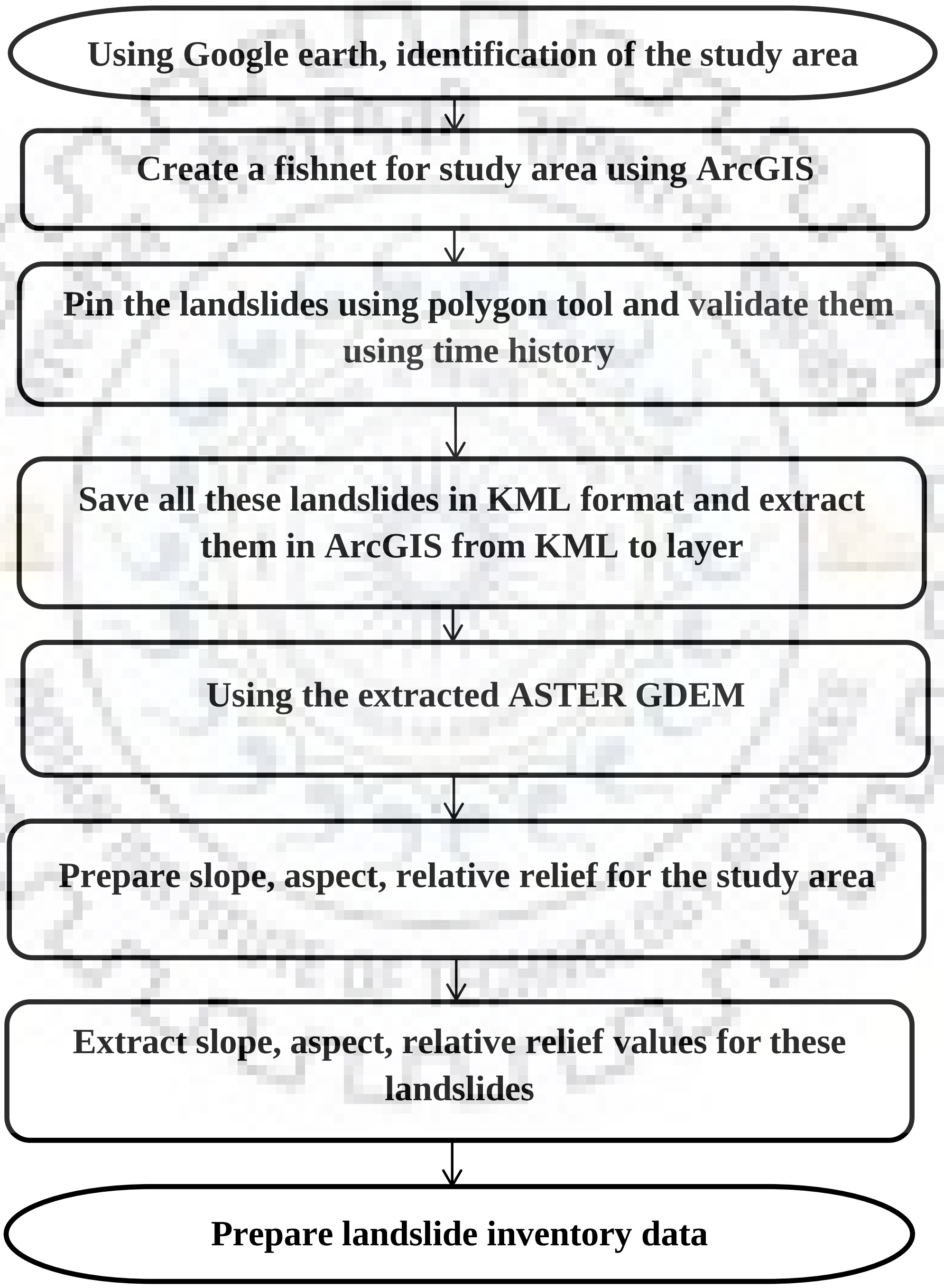
The qualitative approach methods such as the distribution analysis, geomorphic analysis, map combination methods, etc., are most famous in the late 1970s among the geomorphologists and geologists.

Anbalagan et al. (2015) did an extensive study for the identification of landslide hazard zones using landslide frequency ratio fuzzy logic in a GIS environment has been presented for the Lachung valley Sikkim, India. Where the number of hydroelectric projects are proposed in this region. Temporal remote sensing data were used to generate consequential landslide causative factors in addition to landslide inventory. Primary topographic attributes namely slope, aspect and relative relief were derived from the Digital Elevation Model (DEM). Landslide frequency ration approach was acquired to correlate landslide causal factors with landslide incidence. Further, Fuzzy logic method was used for the integration of landslide causative factors in order to present the landslide hazard zones. Fuzzy memberships were derived from the landslide frequency ratio values. Different gamma values are used in the fuzzy gamma integration process, which resulted in different landslide hazard index maps. Receiver operating characteristic curves were prepared to examine the consistency of the resulting landslide index maps.

Geomorphological approach depends on the knowledge, experience and skills of investigators (Guzzetti et al., 1999). Landry (1979), Meneroud and (Calvino 1976), Hearn (1995) and Leroi (1996), these are few scientists who developed landslide susceptibility zonation maps using Geomorphological approach.

3.1 General:

This present chapter covers the steps and methods involved in the preparation of landslide inventory.



Flowchart for preparing landslide inventory

The identification of landslides is done by using Google earth. Landslides could be identified in details by using the past imageries and with the help of polygon tool. Where the preparation of landslide inventory is onerous, and has to follow several steps.

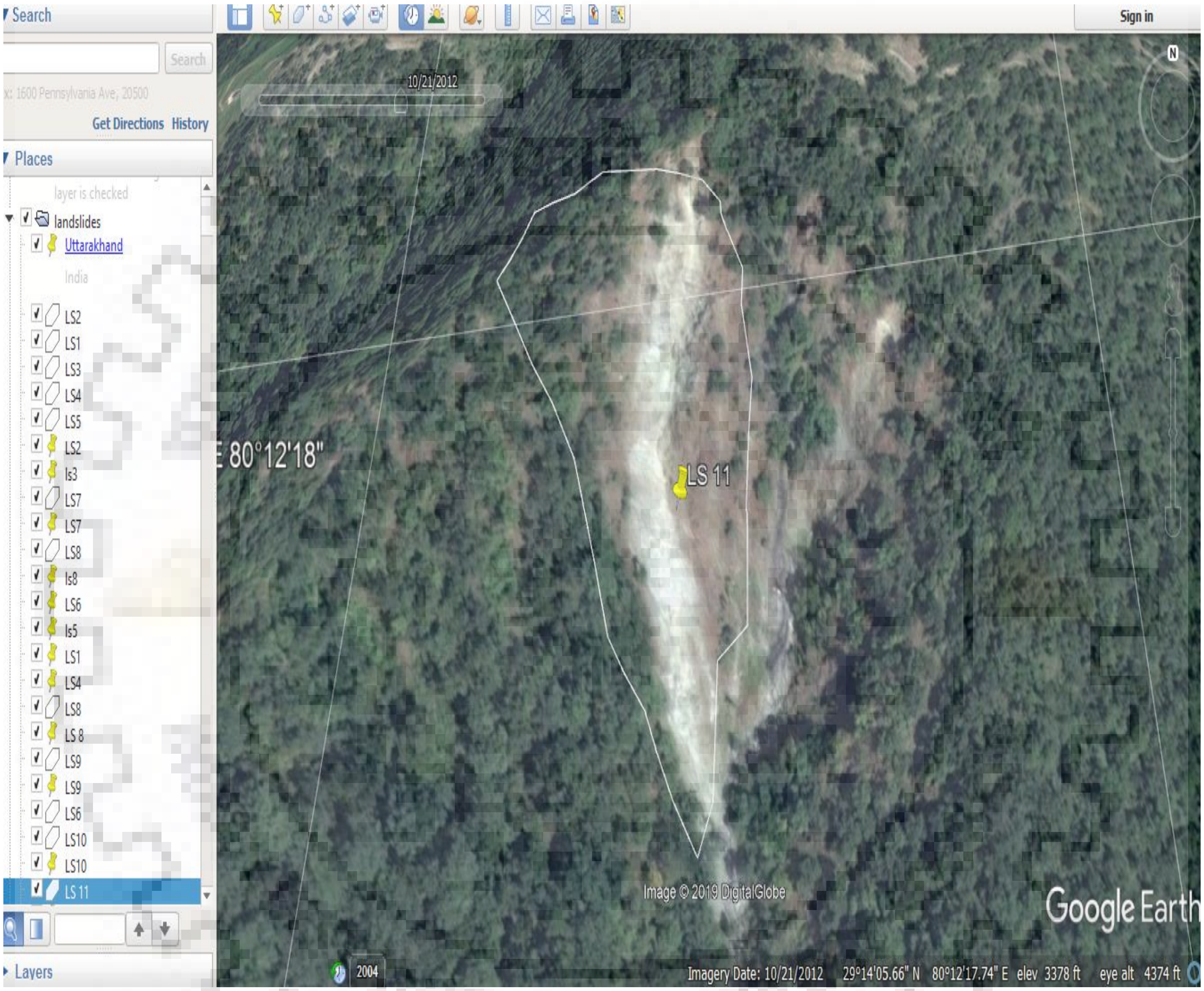


Figure 3.1: Process for the collection of landslides (Source: Google Earth)

Fig 3.2(a)

Fig3.2(b)

Fig 3.2 (c)

Fig3.2 (d)

Figure 3.2: Images of various Landslides (Source: Google Earth).

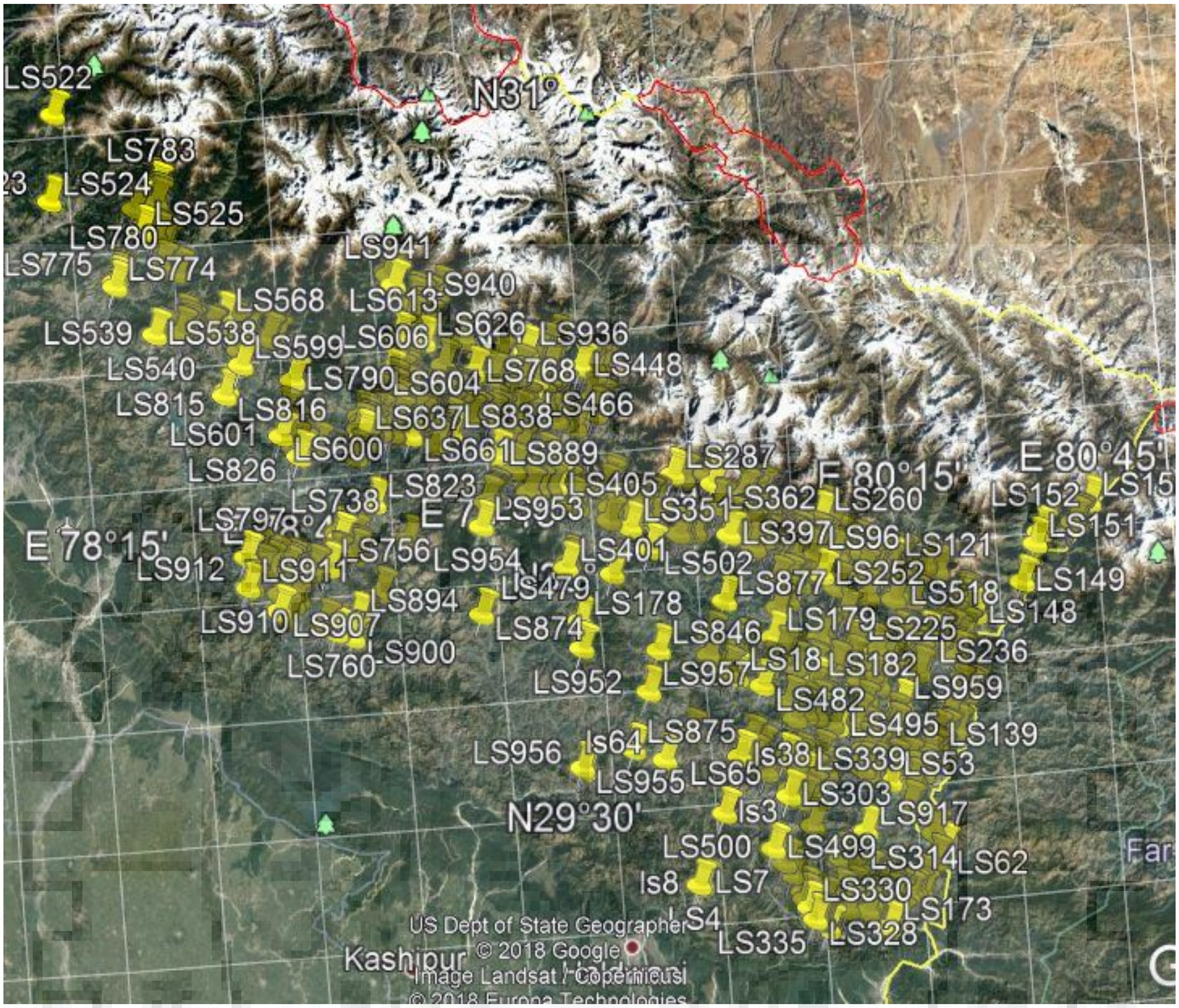


Figure 3.3: A collection of Landslide data from Google Earth (Source: Google Earth).

3.2 Preparation Landslide Inventory Data:

Basically, for preparation of landslide inventory data, the study area should be marked in Google earth and then locate landslides in the study area. Using the help of a polygon tool we can mark the landslides. And using the time historical imagery tool we can validate the landslide. Now data is saved in a KML format, with the help of ArcGIS after locating all landslides export them and convert the KML format file to layer format in ArcGIS. The geographical projection system should be specified for the study area.

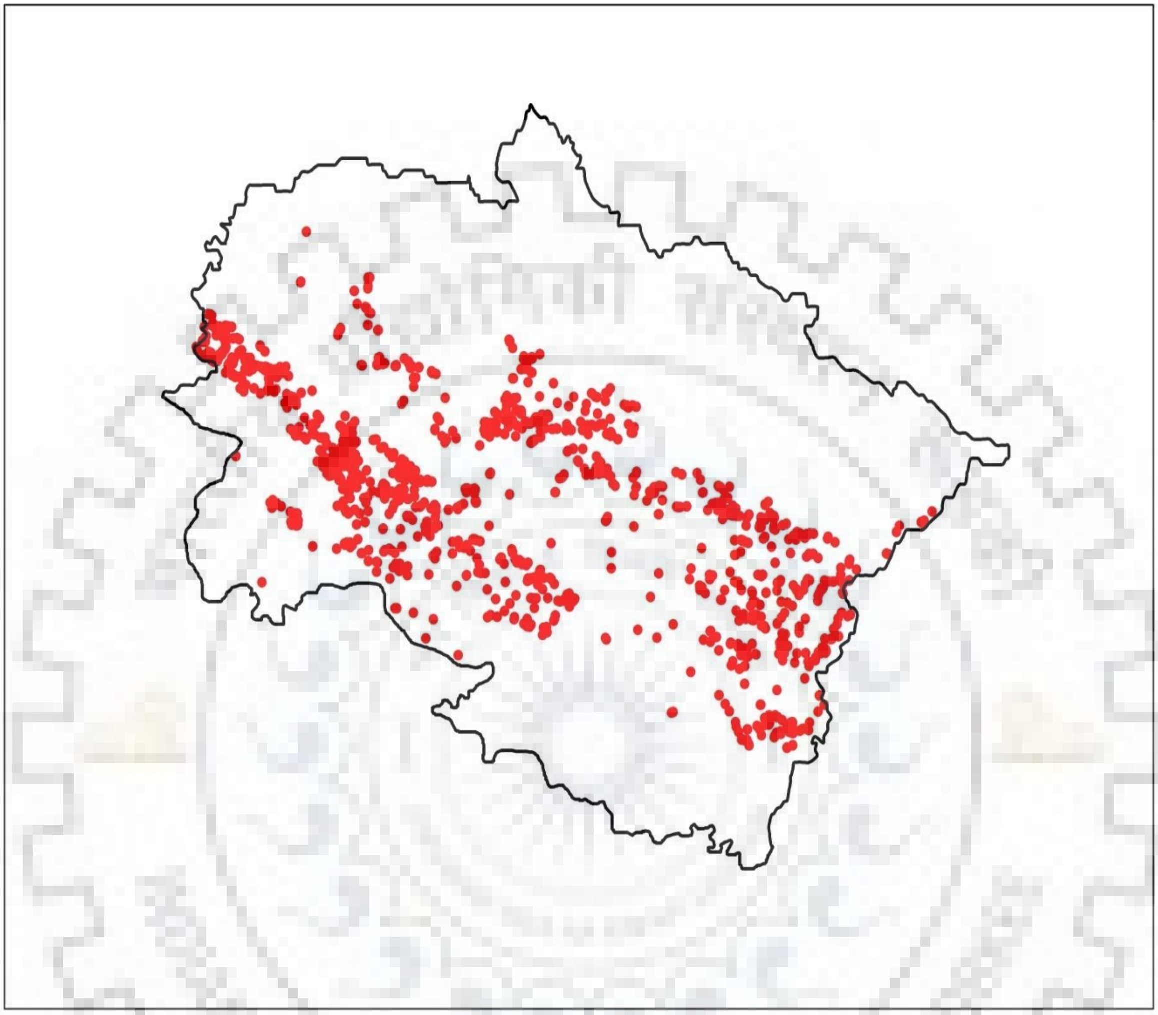


Figure 3.4: Digitized landslides in the study area.

Now with the help of ArcGIS, the attribute table containing a list of the entire landslide is prepared. The latitudes and longitudes are added with the help of the “add field” tool. This is the part of landslide inventory. A figure (3.5) is shown below having latitudes and longitudes for the landslides.

Extract_Points_1

OID *	Shape *	Name	Lat	Long
1	Point Z	Uttarakhand	79.0193	30.06675
2	Point Z	LS2	80.22777	29.25495
3	Point Z	ls3	79.74894	29.43504
4	Point Z	LS7	79.67776	29.29218
5	Point Z	ls8	79.67668	29.29088
6	Point Z	LS6	80.16113	29.2164
7	Point Z	ls5	80.14777	29.22085
8	Point Z	LS1	79.74354	29.76564
9	Point Z	LS4	79.67107	29.28992
10	Point Z	LS 8	80.14567	29.22405
11	Point Z	LS9	80.15905	29.21651
12	Point Z	LS10	80.19793	29.23098
13	Point Z	LS 11	80.20718	29.23313
14	Point Z	LS12	80.10891	29.5233
15	Point Z	LS13	80.13954	29.52687
16	Point Z	LS14	80.13834	29.52724
17	Point Z	LS15	80.10347	29.49949
18	Point Z	LS16	79.78417	29.74249
19	Point Z	LS 17	79.7935	29.73731
20	Point Z	LS18	79.80694	29.71503
21	Point Z	LS19	79.78588	29.72714
22	Point Z	LS20	79.42461	30.13253
23	Point Z	ls21	79.96258	29.64116
24	Point Z	LS22	79.93989	29.53395
25	Point Z	ls23	79.95506	29.51956
26	Point Z	LS24	79.97511	29.5167
27	Point Z	LS25	79.94068	29.52286
28	Point Z	LS26	80.15832	29.25617
29	Point Z	LS27	80.15666	29.25489
30	Point Z	LS28	80.15992	29.25447

0 (0 out of 2190 Selected)

Figure 3.5: List of Landslides with Latitudes and Longitudes (Source: ArcGIS).

For the slope, aspect, relative relief values the DEM data is imported to ArcGIS. Using DEM create a slope, aspect, relative relief layers and using a tool "extract by points" the values are extracted for each layer respectively.

A figure (3.6) of landslide inventory containing the longitudes & latitudes, slope values, aspect values, relative relief values.

	A	B	C	D	E	F
1	Landslide	Longtitud	Latitude	Relative	Aspect	Slope
2	LS1	79.7435	29.7656	1549	190.993	31.28
3	LS2	80.2278	29.2549	1303	169.732	50.27
4	LS3	79.7489	29.435	1790	193.57	7.29
5	LS4	79.6711	29.2899	1550	205.327	51.2
6	LS5	80.1478	29.2208	572	177.248	41.78
7	LS6	80.1611	29.2164	529	175.641	43.82
8	LS7	79.6778	29.2922	1428	166.206	36.42
9	LS8	80.1457	29.224	641	242.745	38.53
10	LS9	80.159	29.2165	505	203.552	36.13
11	LS10	80.1979	29.231	846	121.504	25.08
12	LS 11	80.2072	29.2331	1090	166.845	48.99
13	LS12	80.1089	29.5233	516	213.887	34.7
14	LS13	80.1395	29.5269	796	190.284	45.94
15	LS14	80.1383	29.5272	795	211.209	34.5
16	LS15	80.1035	29.4995	767	171.31	44.82
17	LS16	79.7842	29.7425	1538	191.96	41.68
18	LS 17	79.7935	29.7373	1427	210.069	15.78
19	LS18	79.8069	29.715	1115	208.009	24.55
20	LS19	79.7859	29.7271	1081	215.647	27.6
21	LS20	79.4246	30.1325	1514	223.939	52.66
22	LS21	79.9626	29.6412	741	130.544	25.11
23	LS22	79.9399	29.534	1330	223.939	44.51
24	LS23	79.9551	29.5196	842	174.742	35.08
25	LS24	79.9751	29.5167	916	178.727	21.12

Figure 3.6: A Landslide Inventory Data (Source: ArcGIS).

3.3 General:

The methodology adopted for the present study is qualitative approach, which depends on map combination method for (LSZ) Landslide Susceptibility Zonation Mapping. This is a straight forward approach for calculating Landslide Susceptibility Zonation. Where the effective factors are incorporated as thematic layers and weights, rankings are given based on their effect causing landslides. Hence this method is also known as the weighting and ranking approach which was first proposed by Ven Westen and Soeters in 1996 and since then widely used by (Joshi and Gupta, 1990; McKean et al., 1991; Anbalagan, 1992; Sarkar and Kanungo, 2004; Champati Ray,2005; Sharma and Pareek, 2008). This method is easy to understand both conceptually and mathematically.

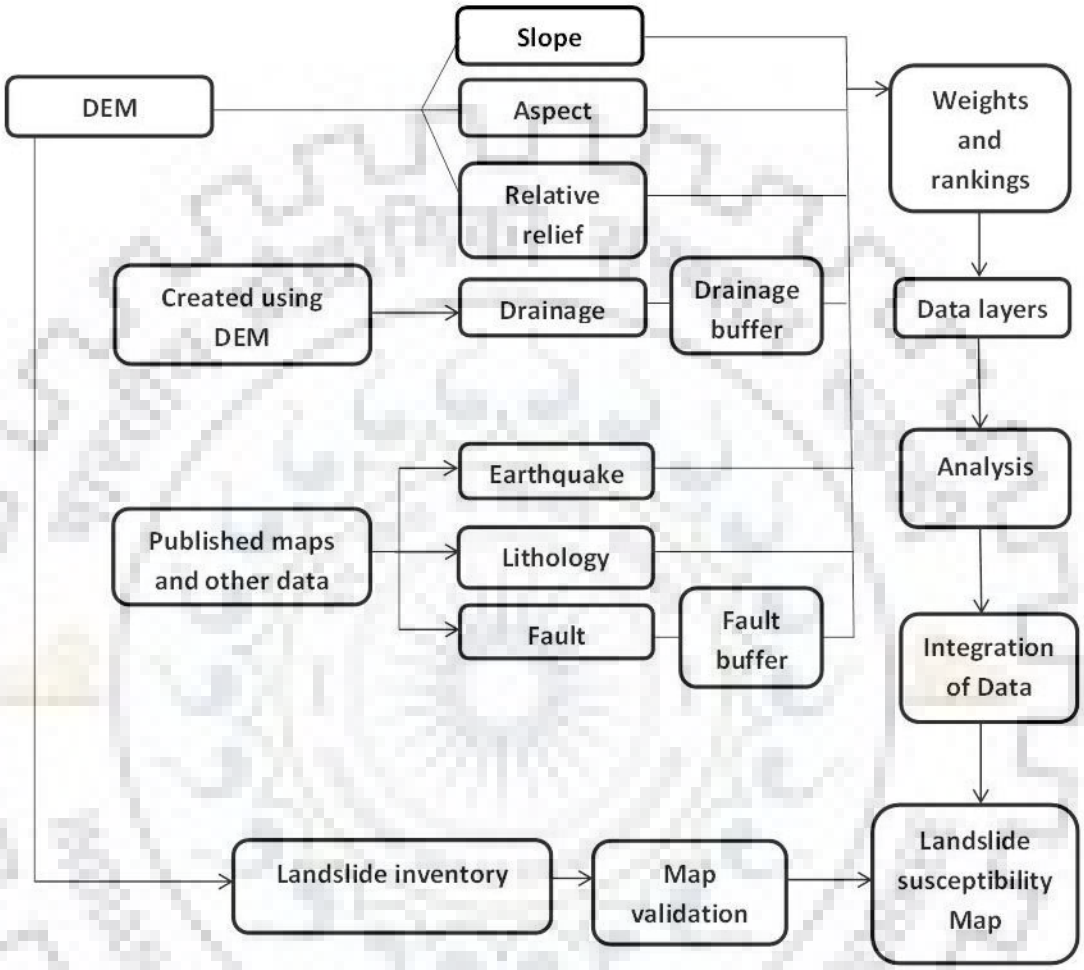
The steps involved in this method are outlined below:

1. Identification of the effective parameters for the study area.
2. Assigning weights to each class.
3. Subdividing each effective parameter into a number of relevant classes.
4. Assigning ranks based on the level of control on landslide occurrence.
5. Estimation and preparation of the weighted maps and numerical data integration and using an ArcGIS platform for obtaining the landslide potential index (LPI).
6. And Landslide Susceptibility Zonation maps (LSZ) are prepared based on the LPI values.

Landslide potential index (LPI) suggests the probability of landslide occurrence based on the superior effective factors in an area. The greater susceptibility to landslide risk is based on the higher value of LPI. The mathematical equation is defined as,

$$LPI = \sum_{i=1}^{n} \sum_{j=1}^{m} R_i \times W_{i.j} \qquad (1)$$

Where R_i and W_{ij} are denoted as the ranks of the landslide affecting factors and weightage of its successive classes respectively.



Flow Chart of steps involved in the preparation of LSZ map

Landslide potential index (LPI) computed by the numerical integration of various thematic layers of the different framework using the above formula in the ArcGIS platform. And for the present study, a total of seven landslide effective factors has been considered and discussed in details below. These parameters have been finalized after a detailed study of the landslide occurrences in the state of Uttarakhand.

3.4 Landslide causative factors used in this study:

- Slope angle.
- Aspect.
- Relative Relief.
- Drainage.
- Lithology.
- Thrusts, faults and lineaments.
- Earthquake.

3.4.1 Slope:

The slope is the key parameter in Landslide Susceptibility Zonation. Slope angle is defined as the change in elevation of a hill or mountain over a particular distance which is measured as angle forms between the surface of the earth and horizontal datum. The slope map was extracted in ArcGIS software with a tool (Spatial Analyst) using raw DEM layer. Generally, slope instability is directly proportional to the angle of slope. In this study, we detected that a maximum number of landslides lies in between where the slope is greater than 30° (degrees). The figure (3.7) below give detailed information about the slope map.

3.4.2 Aspect:

Aspect is a key parameter which plays an important role in the analysis of slope stability, where it is one of the controlling factors of the climatic condition of a specific area. It is referred to as the direction of maximum slope of the terrain surface. The Aspect map was extracted in ArcGIS with a tool (spatial analyst) using raw DEM. The Aspect map is a derivative of the Digital Elevation Model. The vegetation and hydrological condition are effected on the sloping surface due to the aspect which causes soil erosion. A table of aspect classes and their directions are shown below:

Table 3.1: Different Aspect classes and their directions.

Aspect values (In degrees)	Direction
1	Flat
0-22.5	North
22.5-67.5	North-East
67.5-112.5	East
112.5-157.5	South- East
157.5-202.5	South
202.5-247.5	West
247.5-292.5	South- West
292.5-337.5	North-West
337.5-360	North

These are divided into 10 different aspect classes, values ranging from 1 – 360 degrees. And directions such as N,N-E,E,S-E,S,S-W,W,N-W,N. The figure (3.8) below gives detailed information about the aspect map.

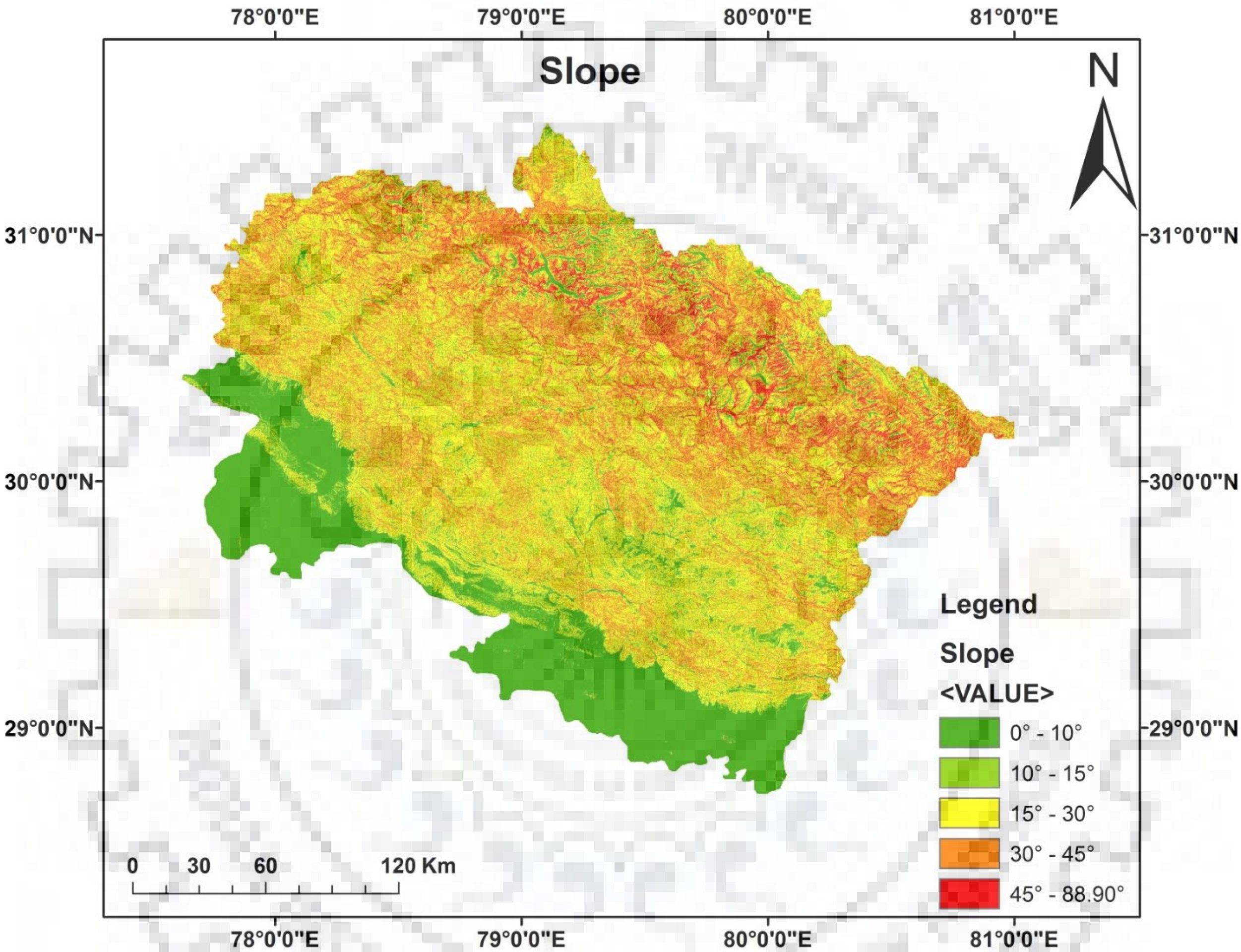


Figure 3.7: Slope map of the study area.

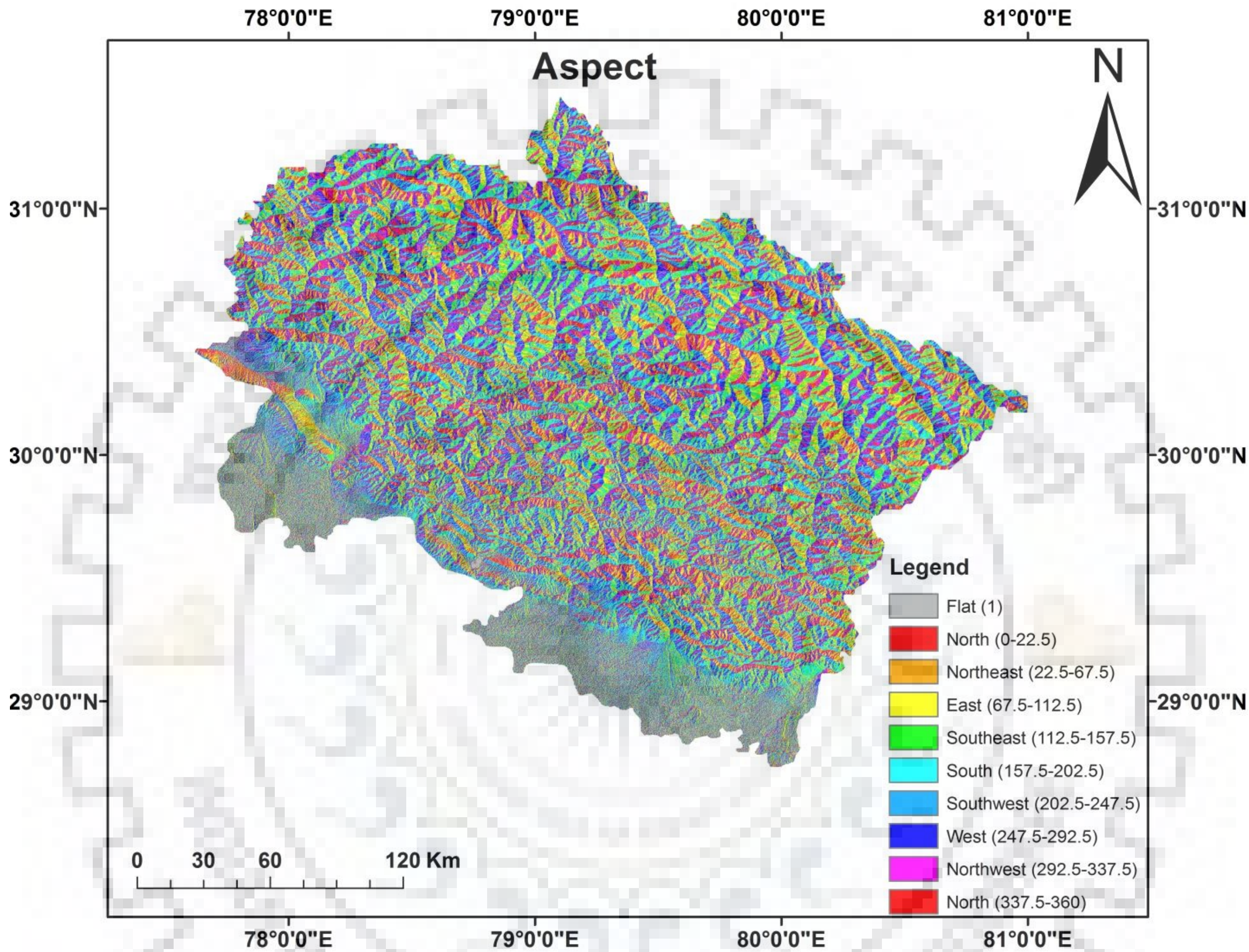


Figure 3.8: Aspect map of the study area.

3.4.3 Relative Relief:

Relative relief layer is a derivate of DEM digital elevation model. It is differences between the highest elevation point and lowest elevation within the selected area. Relative relief is also a key parameter for the occurrence of the landslide. The figure (3.9) of DEM (Digital Elevation Model) shown below using which the relative relief of the study area is calculated. Where in the below figure the highest elevation is 7785 m and the lowest elevation is 74 m.

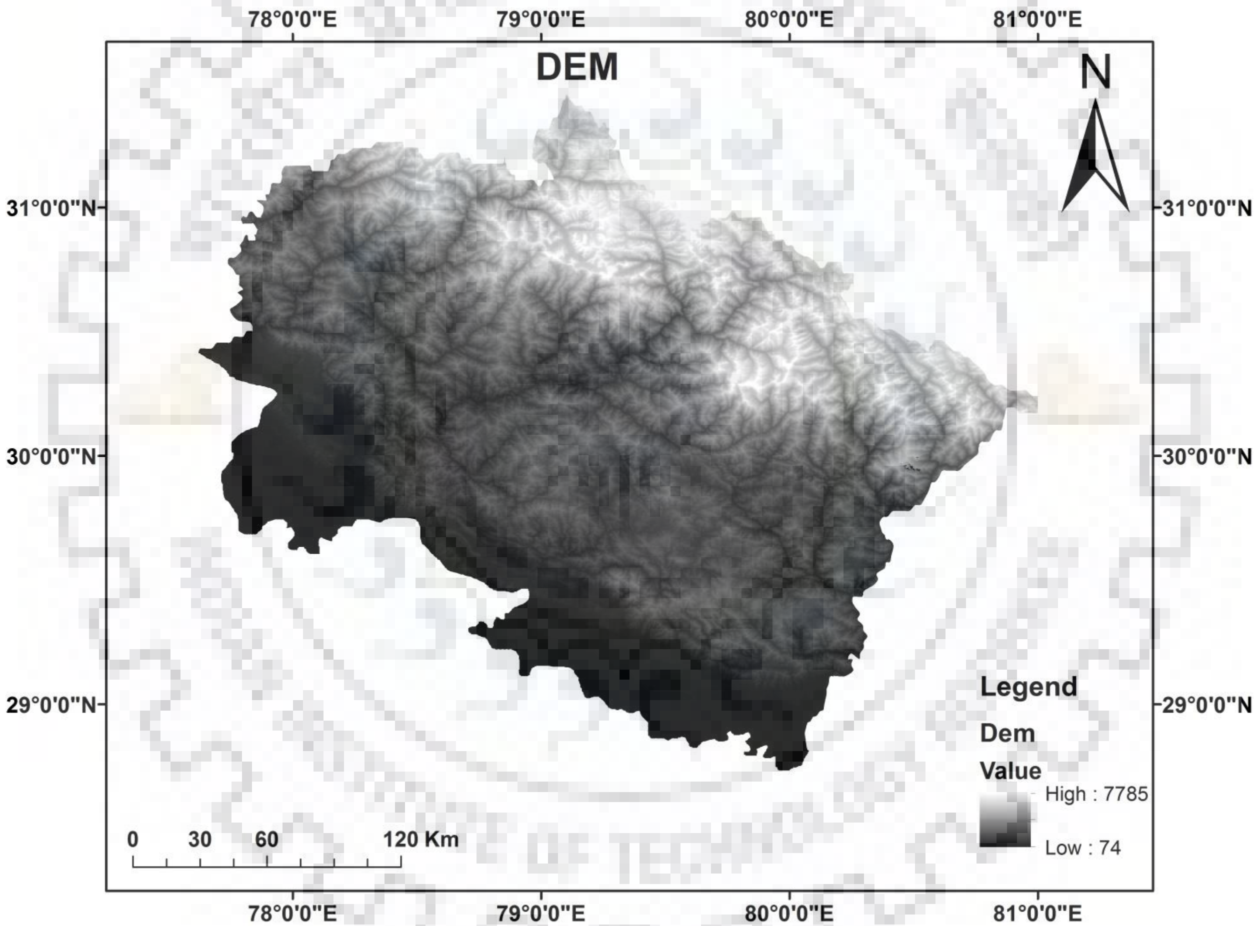


Figure 3.9: Digital Elevation Model (DEM) map of the study area.

3.4.4 Drainage:

Drainage is also a derivate of DEM (Digital Elevation Model). The process of extraction of the drainage data required a -all-inclusive process, with the help of ArcGIS software using a spatial analyst tool. Where select the hydrology option and using available Aster-GDEM as input, we can extract a fill layer from it. In the next step use the fill layer as input and extract flow direction. The flow accumulation is extracted by using flow direction as the input file. Flow direction is used for the next step which involves in the extraction of condition. Flow direction as the input file is used to extract Stream order. The final step involves in the extract of stream feature using the stream order as the input file. Where each file in ArcGIS database are stored in .TIF file format for easy access and accuracy in the calculate of landslide susceptibility mapping .drainage also play a key role along with the slope facing because the drainage network increases the probability of erosion and weathering activities. Hence the drainage system causes the probability for the occurrence of landslides. Figure (3.10) is a drainage map used for the present study area is shown below,

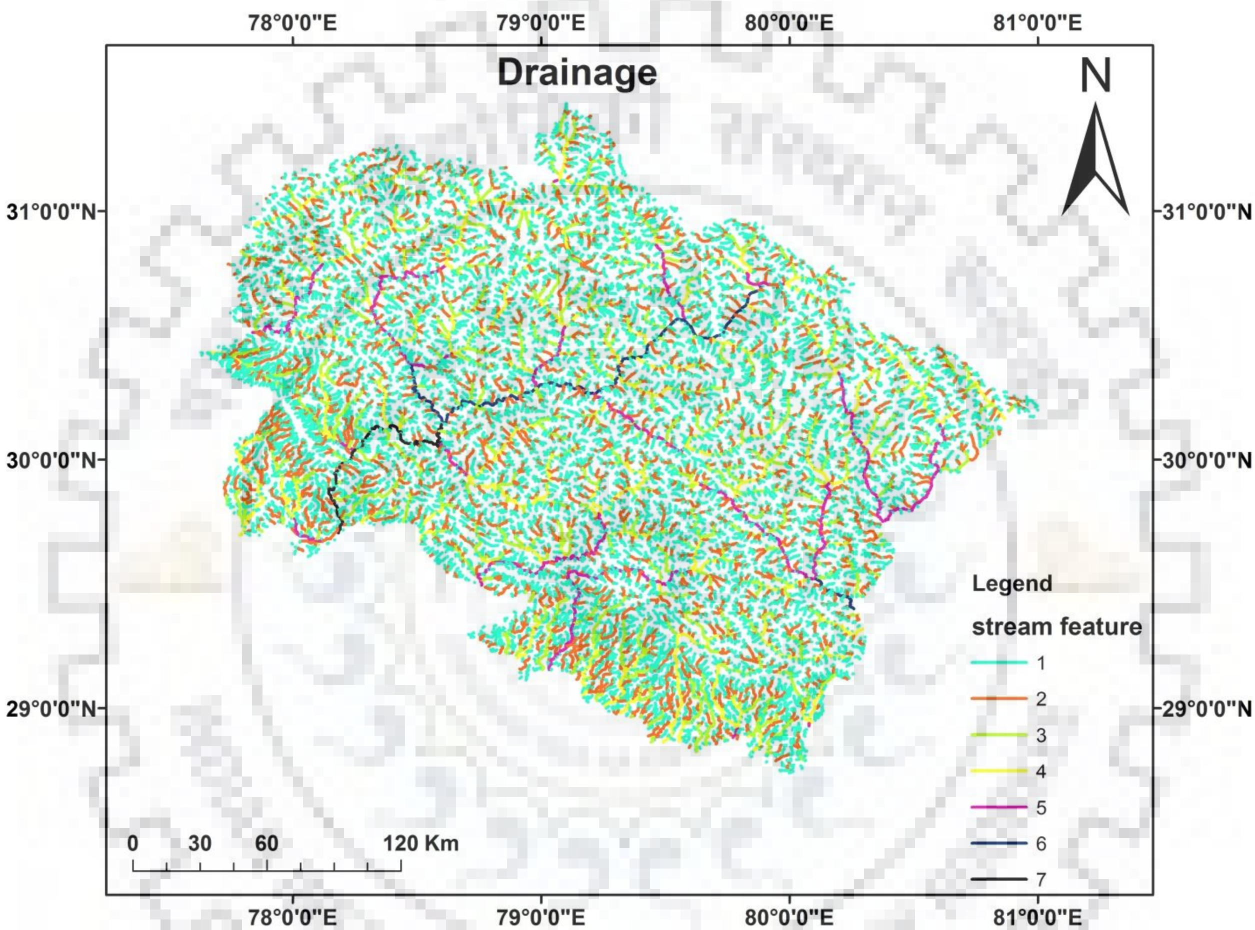


Figure 3.10: Drainage Network map of the study area.

3.4.5 Lithology:

The lithology is the presentation of physical characteristics of soils or rocks. Weaker rocks have high susceptibility for the occurrence of landslides compared to strong rocks.

The lithology of the study area displays four distinct rock types as shown below:

- Sandstone and Shale
- Gneiss
- Phyllite
- Quartzite.

Generally, sandstone is a clastic sedimentary rock which is composed mainly of grain size ranging from (0.0625mm-2mm) rock fragments. Sandstone is composed of quartz or feldspar, these are resistant mineral to cause weathering processes. Sandstone is composed of the same extensive minerals. Sandstone is grey, yellow, red to white in color due to the mineral content and cement.

Shale is also a sedimentary rock, these are fine-grained particles made of silt and clay size minerals which are commonly called as mud. Shale is black, grey, yellow, red in color based on oxygen and organic materials.

The sandstone and shale most commonly found in the lower part of the state Uttarakhand, in places like Haridwar, Nainital, Rudrapur.

Gneiss rocks are high-grade metamorphic rock, which means they are subjected to higher temperatures. Gneiss rocks are formed by the metamorphosis of sedimentary rocks or granite. Gneiss grain size is medium to coarse-grained crystals can be visible to naked eye. Gneiss is one of the hard rocks. Gneiss rocks are dark and light in color.

Gneiss rocks are most commonly available in the upper part of the state Uttarakhand, in places like Uttarkashi, Chamoli, and Pithoragarh.

Phyllite is a foliated metamorphic rock, which had been subjected to pressure, low levels of heat and chemical activity. These rocks are made of flake shape mica minerals. Phyllite was originally a fine-grained sedimentary rock which undergoes a chemical activity transforming from clay to mica .Phyllite are commonly grey, black, and greenish in color

.

Phyllite rocks are most commonly found in the middle part of the state Uttarakhand, in places like Tehri Garhwal, Pauri Garhwal, and Almora.

Quartzite is a metamorphic rock which is formed when quartz-rich chert exposed to high pressure and temperatures. The quartzite rock type not only implies a high degree of hardness but also high quartz content. Quartzite appears like white marble. It can't be scratched by a metal blade. Quartzite is a medium-grained size and the interlocking of quartz crystals is visible through the naked eye. This is a gritty type of rock.

These are commonly white in color, but in some regions, you can find wide color varieties are available.

Quartzite rocks are most commonly found in Dehradun, Champwat in Uttarakhand.

Lithology map is prepared using scanned geology maps available. Where using the coordinate's projection system in ArcGIS coordinates are given to the data layer, with the help of Arc toolbox the shape files of each different rock type are created and merging of all shape files into one layer. The data layer is in shape file formed which is converted into a raster format. Figure (3.11) lithology map of the study area is shown below,

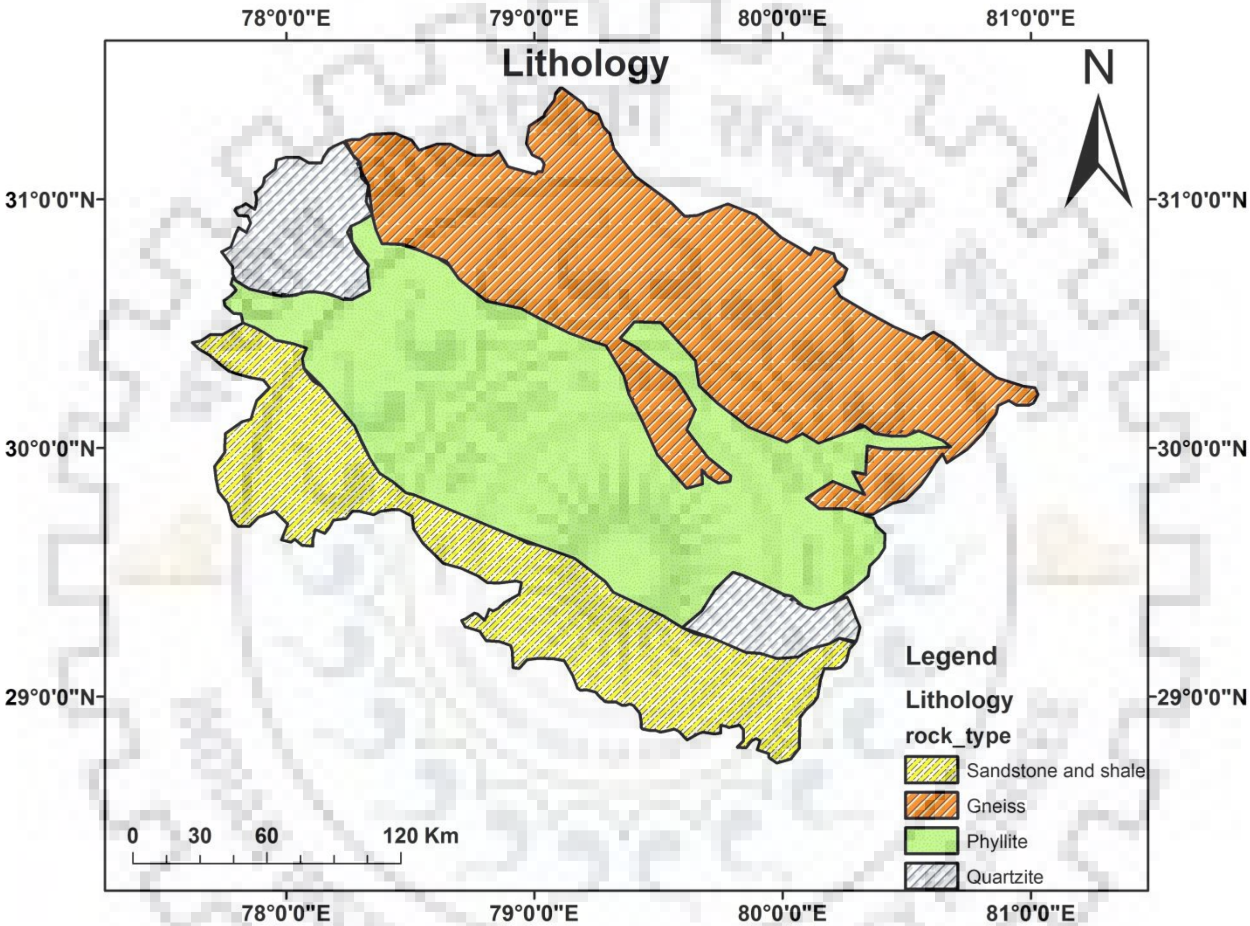


Figure 3.11: Lithology map of the study area.

3.4.6 Thrusts, Faults and Lineaments:

A huge jointed area displaying offsets of a group of hills are called faults. Generally, in geology, a fault is defined as a planar fracture in the volume of rock which has a major displacement as a result of mass–rock movement. The study area has a large number of thrusts, faults and lineaments noted below:

- Thrust MCT
- Thrust MBT
- Thrust MFT
- Thrust NAT
- Thrust SAT
- Thrust Ramgarh
- Thrust N
- Fault N
- AF-Alaknanda Fault
- Lineament N

In the present study area, they are three major thrusts lying like MCT (Main Central Thrust) passing through greater Himalayas, MBT (Main Boundary Thrust) passing through lower Himalayas, MFT (Main Frontal Thrust) is southernmost thrust. These thrusts have a major contribution to the occurrence of landslides. The perpendicular lines to thrusts are the lines displaying lineaments occurring in the study area.

The thrusts and lineaments map is generated using ArcGIS, where shape files of each thrust are merged into one file and projected on the Uttarakhand state boundary shape file and the projection of the coordinate system is done. Figure (3.12) shows thrusts, faults and lineaments map of the study area,

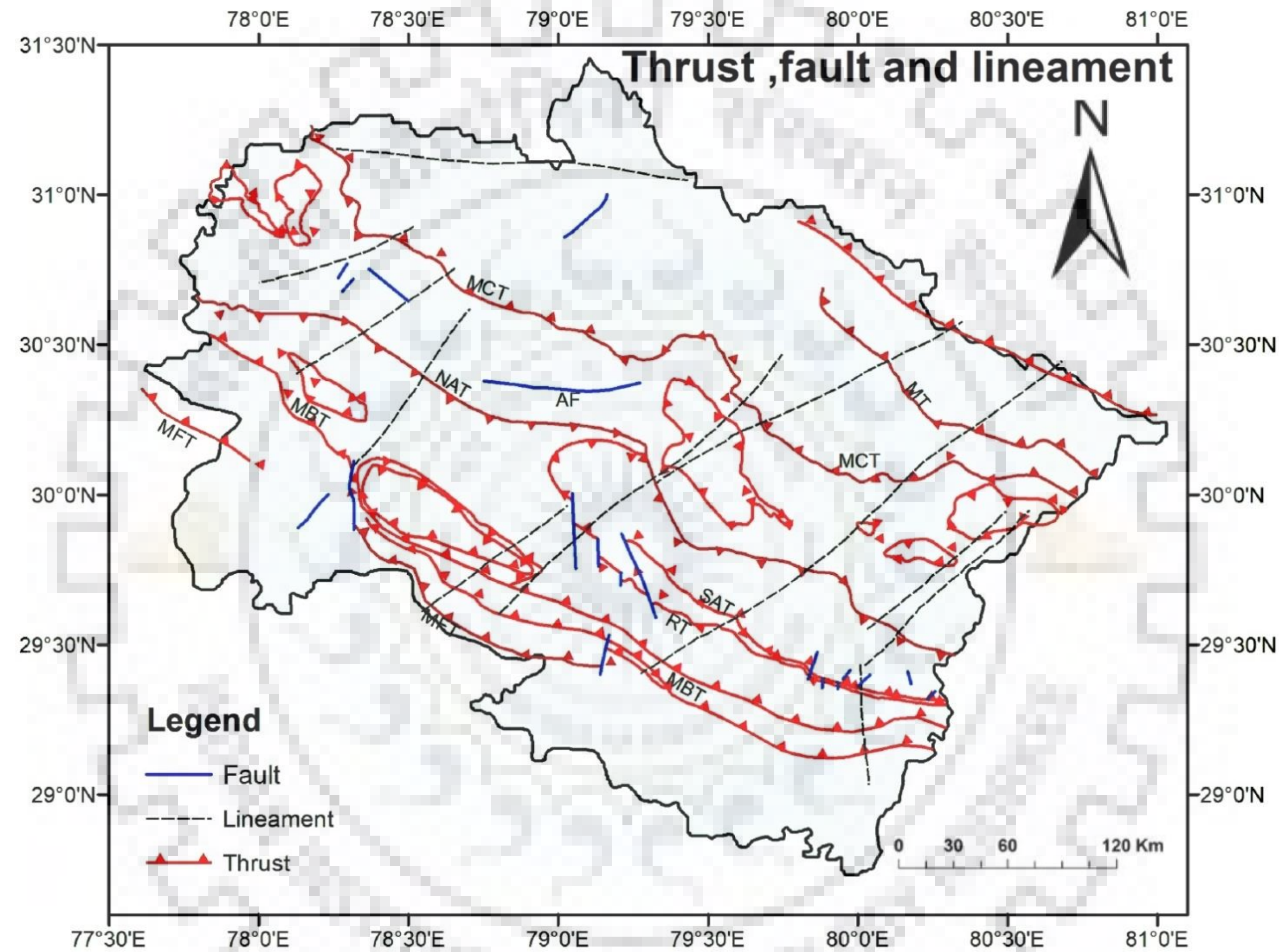


Figure 3.12: Thrusts, faults and lineaments (MT-Martoli Thrust, MCT-Main Central Thrust, AF-Alaknanda Fault, NAT-North Almora Thrust, SAT-South Almora Thrust, RT-Ramgarh Thrust, MBT-Main Boundary Thrust, and MFT-Main Frontal Thrust) map of the study area.

3.4.7 Earthquake:

The earthquake is a key parameter for the occurrence of landslides. Where both the earthquake and landslides are sudden natural disasters, the earthquakes tremors not only create new landslides but also revive the old ones. The study area is under the seismicity intensity zone IV according to the earthquake resistant design code of India [IS 1893(part 1) 2002]. For the preparation of the seismicity map, the data available in the IMD (India Meteorological Department) is collected from the year 1803 which have magnitude > 5.

The data collected from IMD is saved in .CSV files and with the help ArcGIS using a joining tool and projecting the earthquake data on the Uttarakhand state boundary file. Now with the help of interpolation techniques in the remote sensing, .the seismicity map has been generated. In this study, IDW (Inverse Distance Weighted) interpolation technique has been used from the spatial analyst tool from Arc toolbox. The seismicity map is generated based on the magnitudes. Figure (3.13) shows earthquake map of the study area,

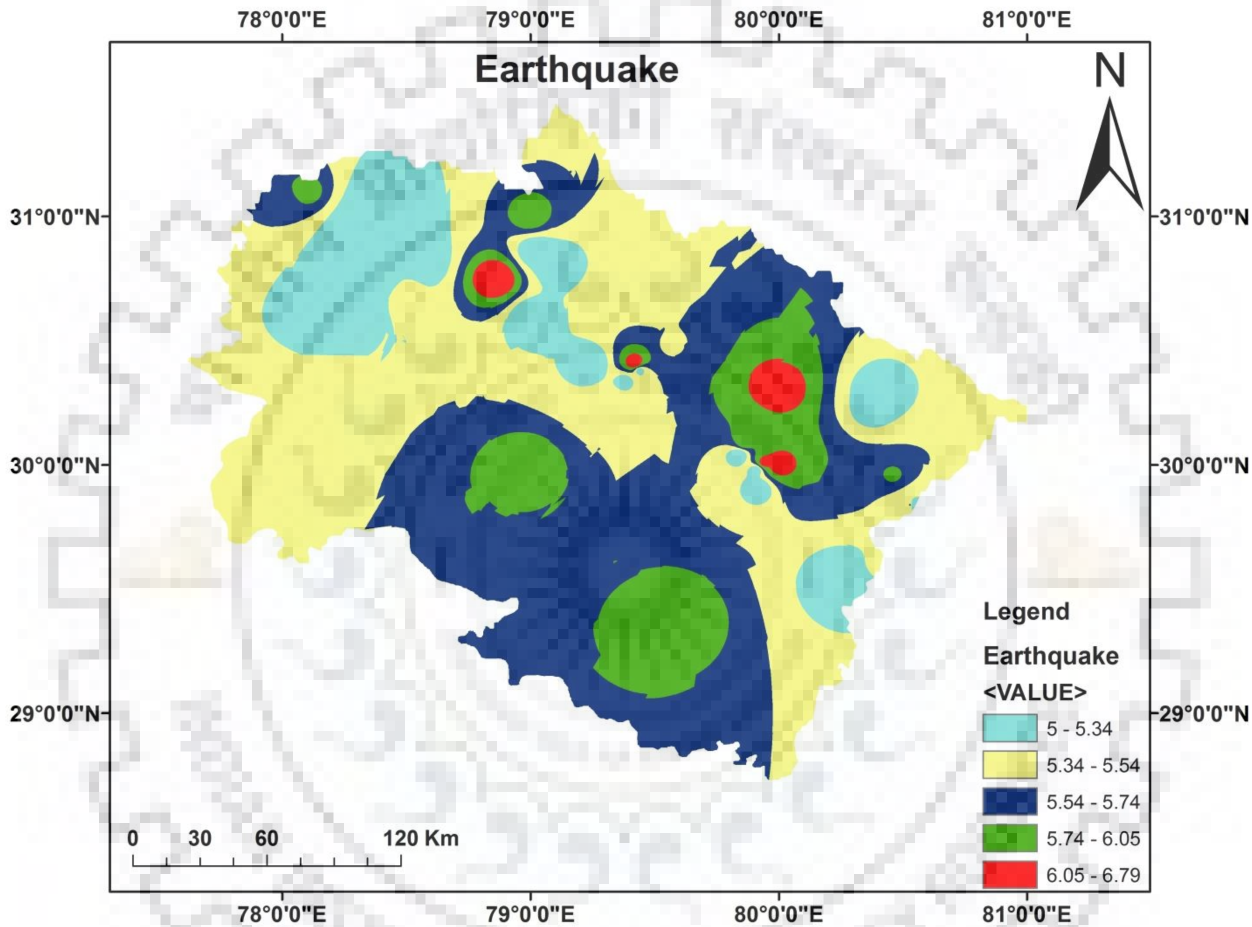


Figure 3.13: Earthquake map of the study area.

4.1 General:

According to the detailed study of the literature review, the qualitative approach is used for present dissertation work for the preparation Landslide Susceptibility Zonation (LSZ) maps. For specifying the probable hazard zones, using LPI (Landslide potential Index) as given in the equation (1) and divided into five different degrees of susceptibility. Hence the calculated landslide potential Index (LPI) is a total relation of Aspect, Slope, Relative relief, Drainage, Lithology, Thrusts and Lineaments, Earthquake of the respective study area used as Thematic layers data integration in a GIS environment. This chapter contains data information about various thematic layers properties, detailed landslide inventory represented as a layer view of the study area, weights and ranks allocated to the causative factors for the preparation of final Landslide Susceptibility Zonation (LSZ) map of the study area.

4.2 Thematic data layers:

For the preparation of Landslide Susceptibility Zonation (LSZ) map, the detailed thematic layers are mandatory, based on all of the parameters of landslide occurrence. These thematic data layers such as aspect map, slope map, relative relief, lithology map, etc. have been prepared using various techniques. In the below chapter, each map is explained in detail.

4.2.1 Landslide distribution map:

A detailed identification of landslides is done by using Google earth. Using this software the landslides are pinned based on the activity with respect to the time history imagery. Identification of existing landslides and preparing the landslide inventory data based on the terrain behavior and geomorphology of the study area. This affected study area is appearing in a bright tone due to a large mass movement and bare land without vegetation and also due to contrast enhancement. A total 2188 number of existing landslides have been identified. Using the ArcGIS a map has been prepared, representing the occurred landslides in the study area.

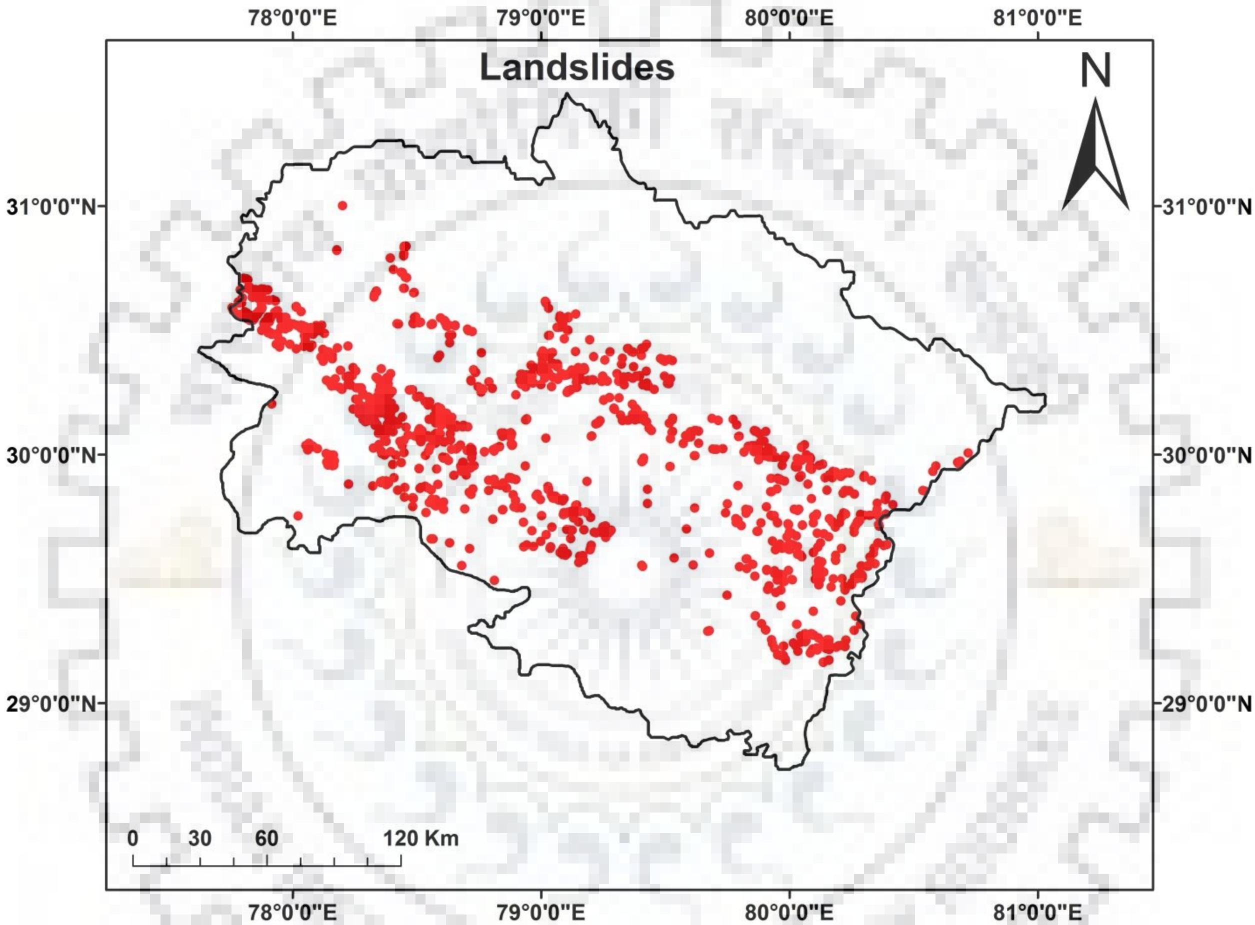


Figure 4.1: Landslide distribution map.

4.2.2 Weighted Slope:

The slope is one of the key parameter contributing to the occurrence of landslides. Based on the observed landslides data, that landslides occur where the slope angle is more than 30°. Hence these angle slopes are more susceptible. Generally, the slope map is prepared from the ASTER GDEM using the ArcGIS software and also plotting landslides points' distribution. The slope map having the range variation of slope angle from (0° -89°) as shown in figure (4.2) below. The weights are assigned based on the gradient angle as shown in the table below for the different classes of slopes. Based on the susceptibility weighted slope map is classified into four different classes such as low, moderate, high, very high.

Table 4.1: Slope classes along with their Weightage

Slope classes	Susceptibility Notation	Weightage
0°-15°	Low	4
15°-30°	Moderate	6
30°-45°	High	8
45°-89°	Very high	9

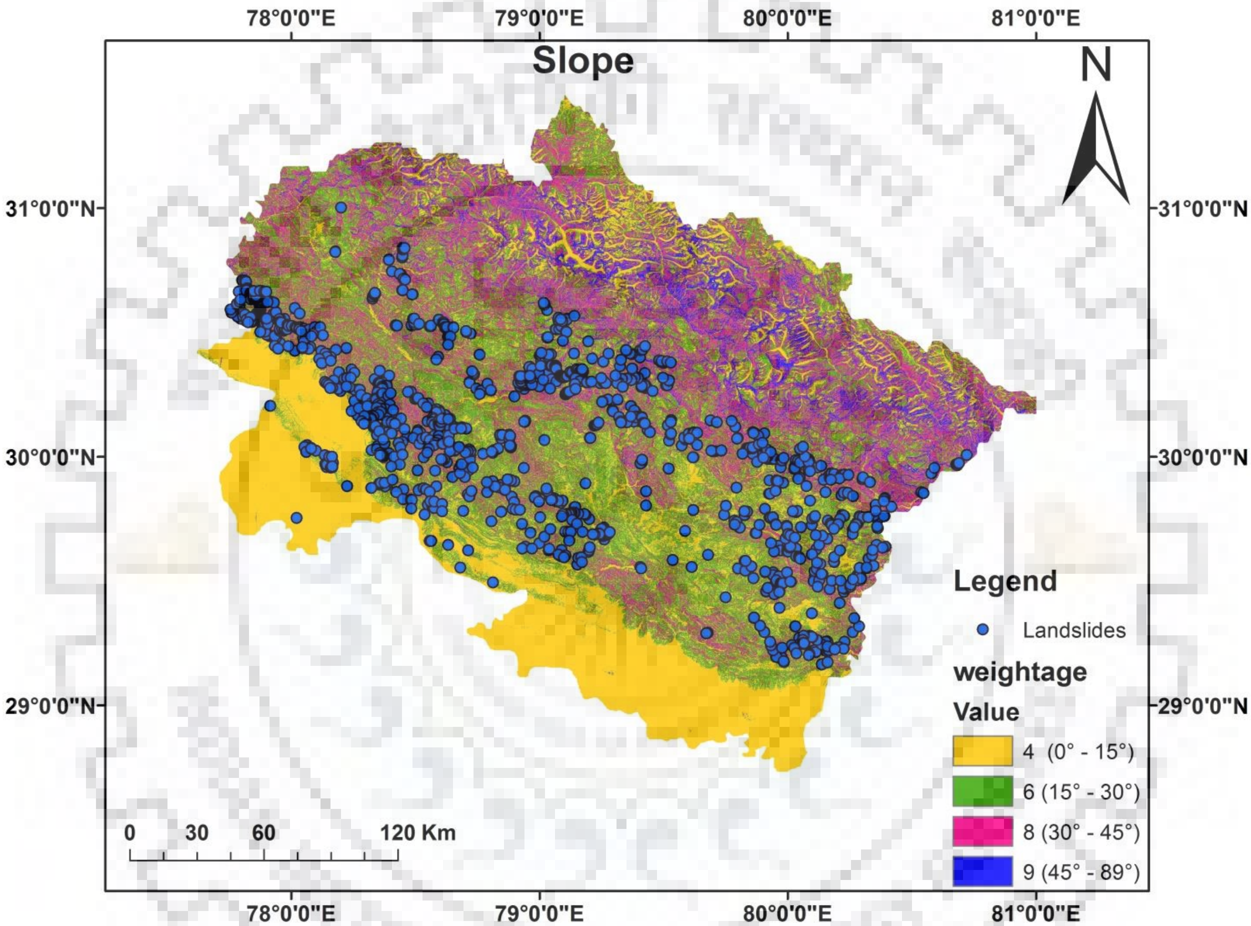


Figure 4.2: Weighted slope map.

4.2.3 Weighted Aspect:

Aspect is a key parameter which plays an important role in the analysis of slope stability, where it is one of the controlling factors of the climatic condition of a specific area. It is referred as the direction of maximum slope of the terrain surface. The Aspect map is prepared from the ASTER GDEM using the ArcGIS software and also plotting landslides point's distribution. The weights are assigned to different aspect value ranges from 1°-360°as shown in figure (4.3) below. The weighted aspect map is classified into four different classes ,based on the susceptibility such as low, moderate, high, very high as shown in the below table (4.2)

Table 4.2: Aspect classes along with their Weightage.

Aspect values	Susceptibility Notation	Weightage
1°-90°	Low	3
90°-180°	Moderate	7
180°-270°	High	9
270°-360°	Very Low	1

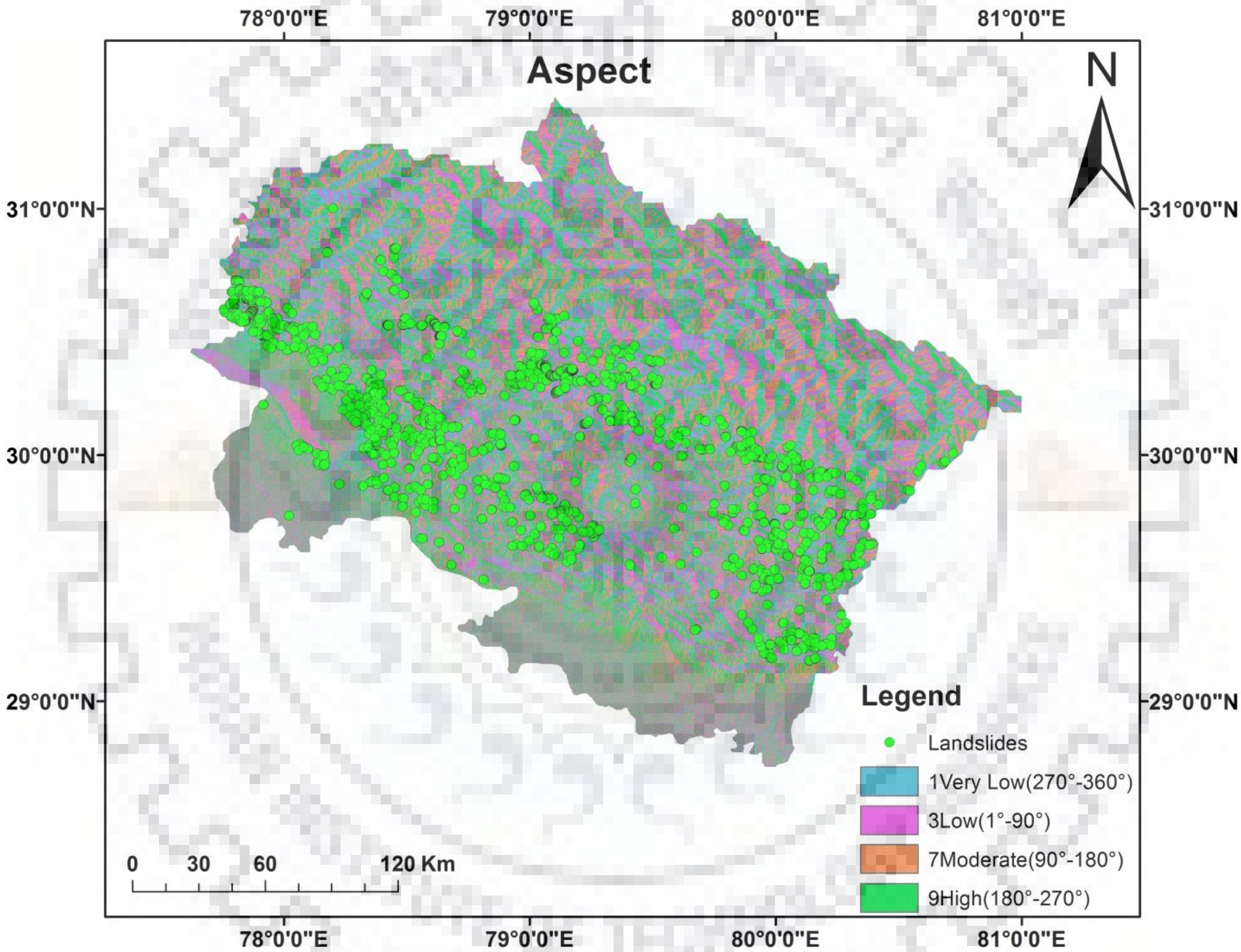


Figure 4.3: Weighted Aspect map.

4.2.4 Weighted Relative relief:

Relative relief is also a key parameter for the occurrence of the landslide. Generally, where the higher elevation area, it is a prone zone for landslides. The relative relief map is prepared from the ASTER GDEM using the ArcGIS software and also plotting landslides point's distribution. The weights are assigned to different relative relief values based on the elevations. The weighted relative relief map is classified into different classes as high, moderate, low, very low based on the susceptibility as shown in the below table (4.3)

Table 4.3: Relative relief classes along with their Weightage.

Relative relief values(meters)	Susceptibility Notation	Weightage
74-1000m	Very Low	2
1000-2000m	Low	4
2000-3000m	Moderate	6
3000-7785m	High	8

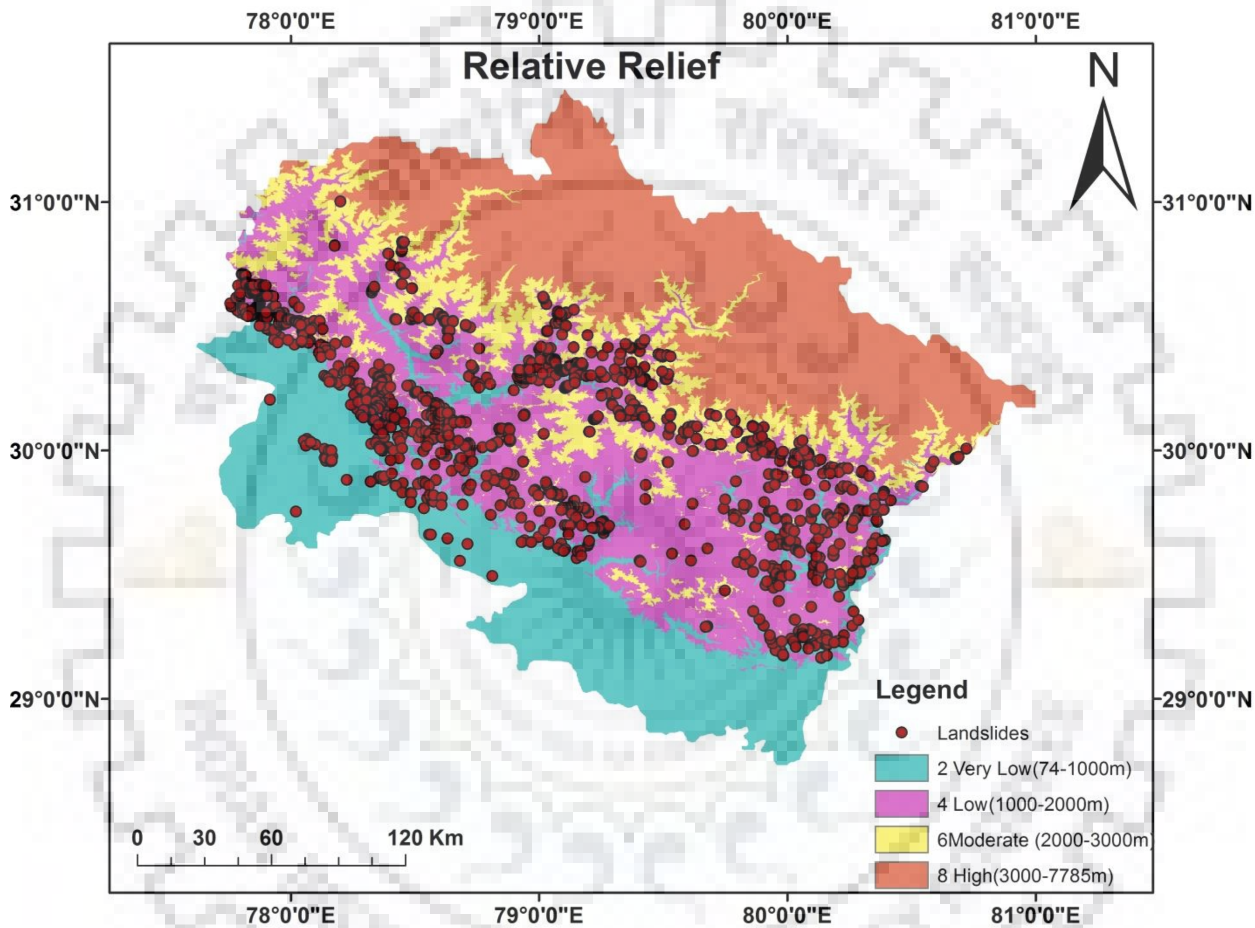


Figure 4.4: Weighted Relative relief map.

4.2.5 Weighted Drainage:

The drainage layer is also a derivate of DEM (Digital Elevation Model). Drainage plays a key role along with the slope facing because the drainage network increases the probability of erosion and weathering activities. Hence the drainage system has the probability for the occurrence of landslides. Where the study area is large, therefore the drainage network simultaneously will be large. Where the drainage extracted for the present study is polyline but all other input parameters are raster format. Using a Euclidean distance technique from the spatial analyst tool the map is prepared. Generally, Euclidean distance is explained as it is the distance from each cell in the raster to the closest sources, hence in this case source is drainage .where the drainage affects the surrounding area so weights assigned according to the distance from drainage. The lowest weight is assigned to farthest distance from the drainage and the highest weight is assigned to the shortest distance from the drainage. Based on the susceptibility, the weighted drainage map is classified into four different classes shown in the below table (4.4) along with landslide points distribution.

Table 4.4: Drainage classes based on the Euclidean Distance along with their Weightage.

Drainage Euclidean values(meters)	Susceptibility Notation	Weightage
200-3410.47 m	Very Low	1
100-200 m	Low	3
50-100 m	Moderate	5
0-50 m	High	7

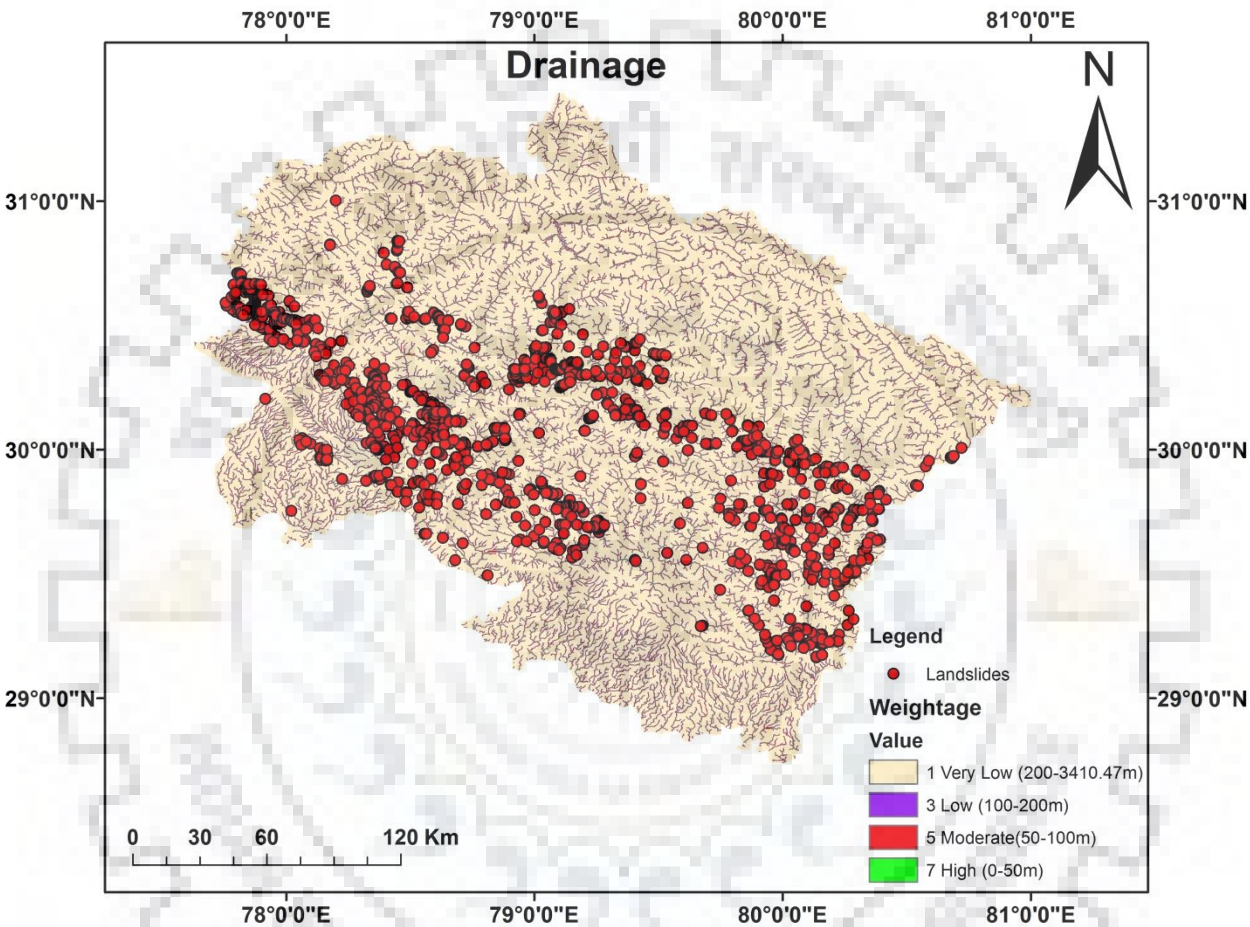


Figure 4.5: Weighted Drainage map.

4.2.6 Weighted Lithology:

Lithology map of the study area is prepared using scanned geology maps available. Where using the coordinate's projection system in ArcGIS coordinates are given to the data layer, with the help Arc toolbox the shape files of each different rock type are created and merging of all shape files into one layer. The data layer is in shape file formed which is converted into a raster format. Where the study area contains rocks types mentioned below, a detailed discussion of rock types and their properties are done in chapter 3. A lithology map is prepared after assigning the weights as shown in the figure (4.6) with landslide point's distribution.

Table 4.5: Lithology classes along with their Weightage

Lithology classes	Weightage
Phyllite	8
Sandstone and shale	6
Quartzite	5
Gneiss	4

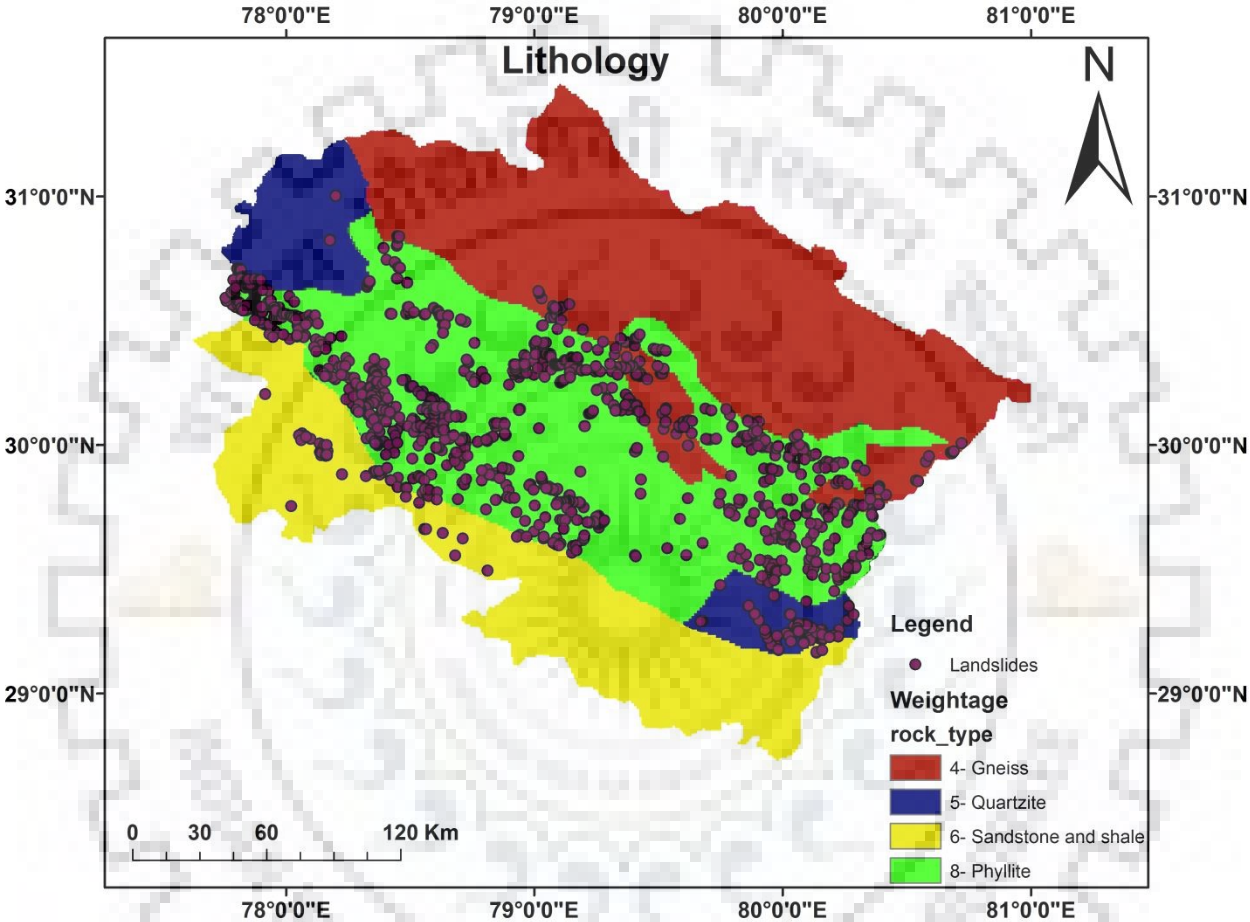


Figure 4.6: Weighted lithology map.

4.2.7 Weighted Thrusts, Faults and Lineaments:

Thrusts, faults and Lineaments are useful for the study of the seismicity at a particular area potential to generate great earthquakes in the future. The earthquakes tremors not only active new landslides but also revive the old ones. A detailed discussion of major thrusts and lineaments had been explained in the previous chapter. Thrusts and lineaments data was collected from various published maps.

Using a Euclidean distance technique from the spatial analyst tool the thrusts and lineaments map is prepared. The weights are assigned based on the area lying near to thrusts having high weights and the area lying farther having fewer weights.

The weighted thrusts and lineaments map is divided, based on the susceptibility into five different classes as shown in the below table (4.6) along with landslide points distribution.

Table 4.6: Thrusts and Lineaments based on the Euclidean Distance *(*Km*)* classes along with their Weightage.

Thrusts and Lineaments Euclidean Distance(Km)	Susceptibility Notation	Weightage
>10km	Very Low	1
6-10km	Low	3
3-6km	Moderate	5
1.5-3km	High	7
0-1.5km	Very high	9

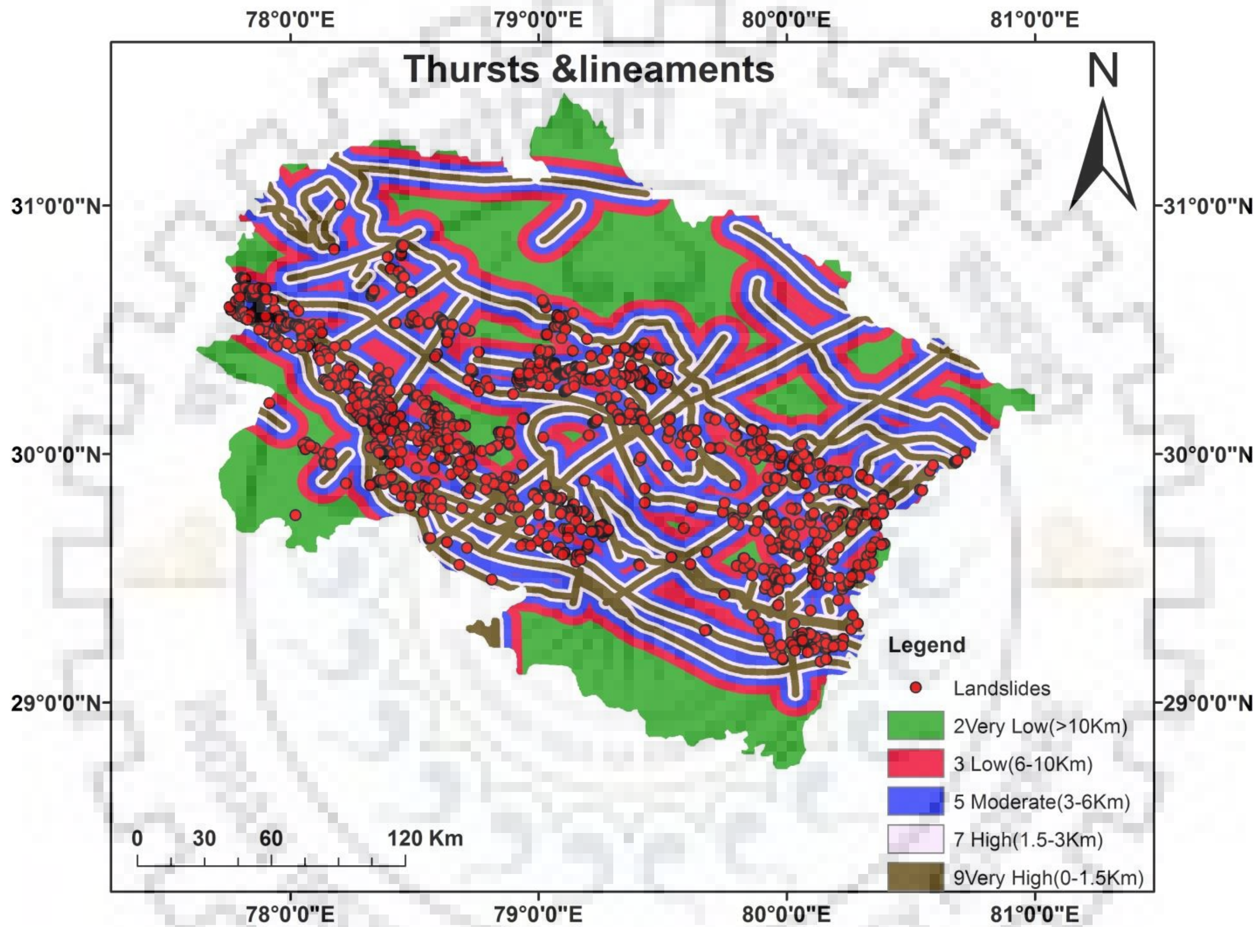


Figure 4.7: Weighted Thrusts and Lineaments map.

4.2.8 Weighted Earthquake:

The earthquake is a key parameter for the occurrence of landslides. Where both the earthquake and landslides are sudden natural disasters, the earthquakes tremors not only active new landslides but also revive the old ones. The data collected from the Indian Metrological Department (IMD) and saved in (.CSV files) and with the help ArcGIS using a joining tool and projecting the earthquake data on the Uttarakhand state boundary file. Now with the help of interpolation techniques in the remote sensing, we can generate the seismicity map. In this study, we used an IDW (Inverse Distance Weighted) technique from the spatial analyst tool from Arc toolbox. The seismicity map is generated based on the magnitudes. The weights are assigned based on the magnitudes of the earthquake.

Based on the susceptibility, the weighted earthquake map is categorized into five different classes, as shown in the below table (4.7) and plotting the landslide points distribution.

Table 4.7: Earthquake classes along with their Weightage.

Earthquake	Susceptibility Notation	Weightage
5-5.35	**Very Low**	**1**
5.35-5.57	**Low**	**3**
5.37-5.82	**Moderate**	**6**
5.82-6.79	**High**	**9**

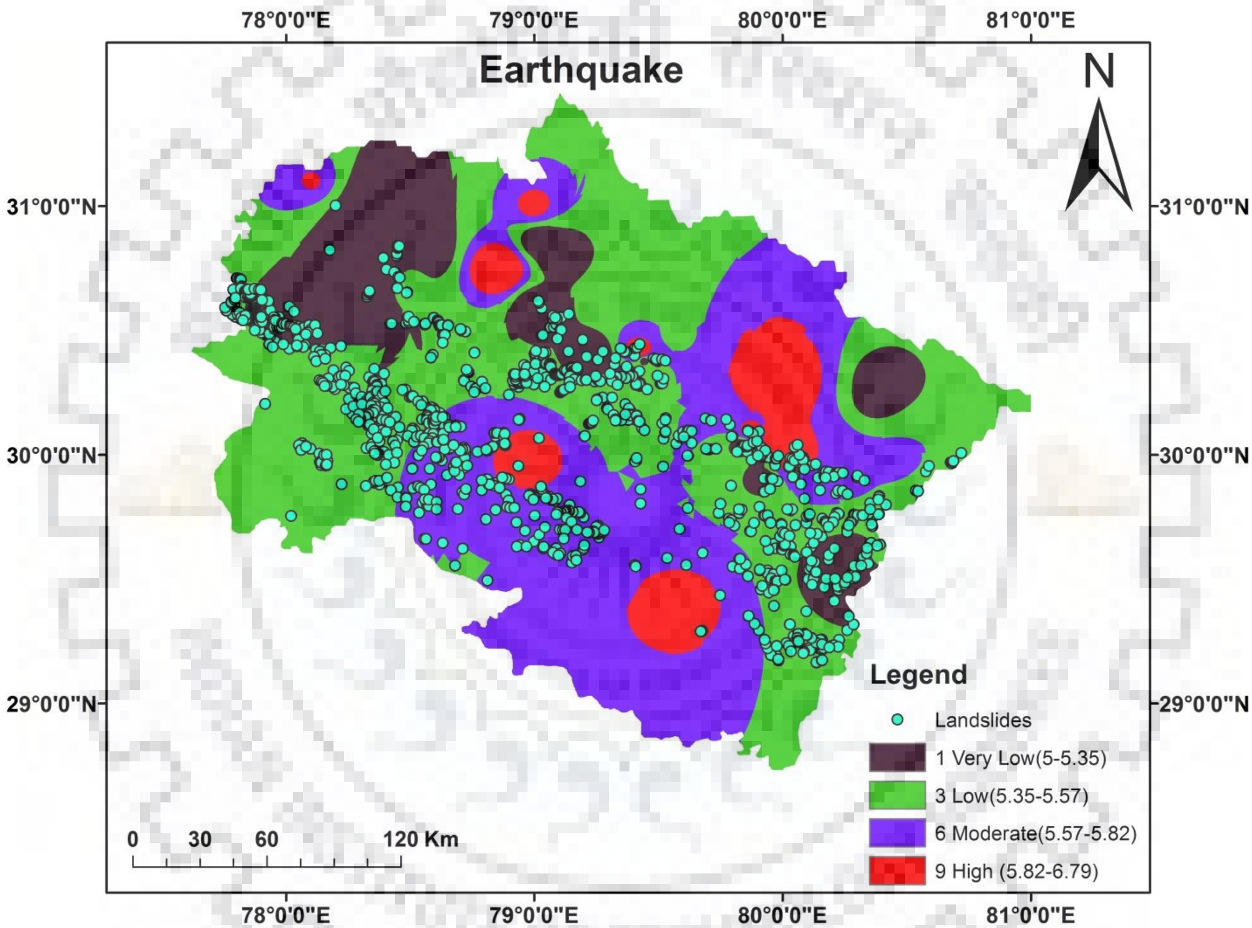


Figure 4.8: Weighted Earthquake map.

4.3 Procedure for Landslide Susceptibility Zonation:

Each thematic data layers are prepared and included in the ArcGIS for the data integration to create a landslide susceptibility map of the study area. The process for the preparing of the susceptibility map includes a lot of onerous internal data run process based on the number of layers. Using the Arc Toolbox select the raster calculator from spatial analyst tool. Raster calculation is process where three or more input data layers needed to create and execute map algebra expression using python syntax in a calculator type interface, and the output will be in the raster format.

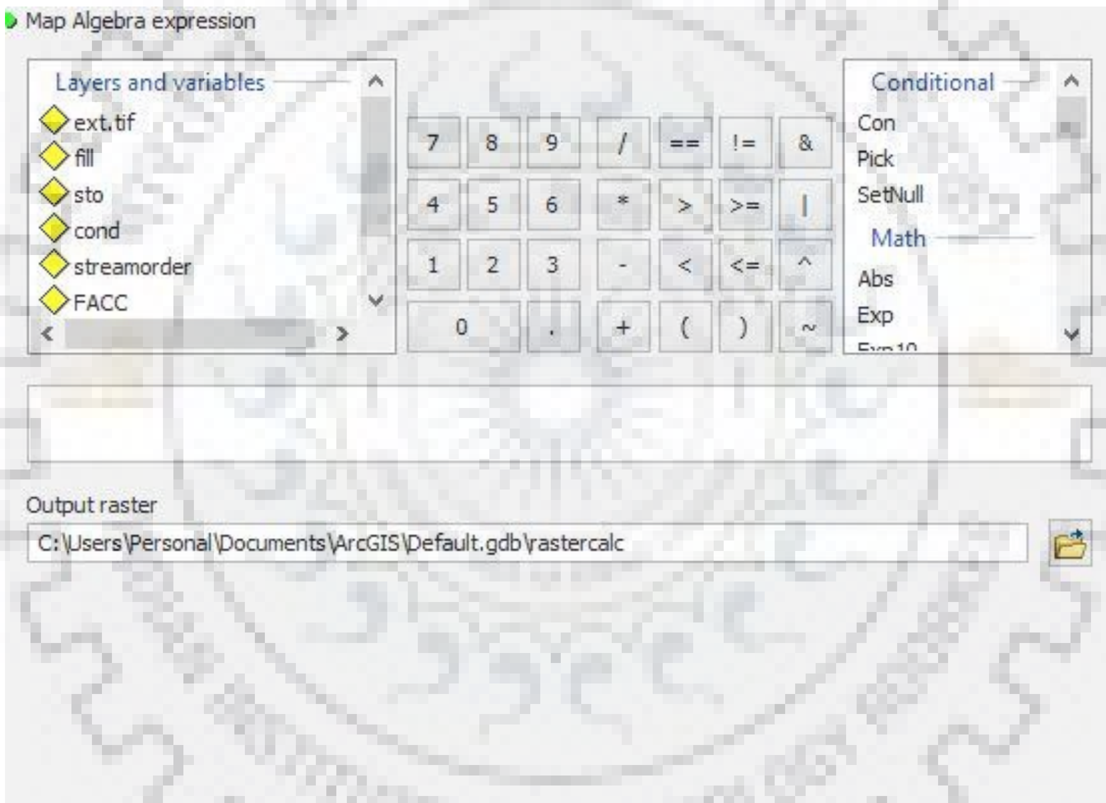


Figure 4.9: Raster calculation dialog box (Source: ArcGIS)

Using the variables and layers list from the selection of variables and datasets to be used in the expression. Mathematical operators and numerical values can also be to the expression by using the respective options in the tool dialog box.

The data should be specified inside the quotes (“”) such as the weighted thematic data layers and the mathematical expressions.

The each weighted thematic layers are loaded in the calculation. The ranks of each layer are assigned based on the causative parameter, for occurrence of the landslide. The data integration is done by using mathematical calculations, around eight different classes of landslide susceptibility are identified after a detailed evaluation the classes are compressed into five different classes. The landslide potential index (LPI) and Landslide Susceptibility Zonation (LSZ) is prepared using the equation (1).The table of various causative parameters and assigned ranks is provided below:

Table 4.8: Causative parameters and assigned ranks.

Serial. No	Causative Parameters	Ranks
1	Slope	7
2	Earthquake	6
3	Lithology	5
4	Thrusts and Lineaments	4
5	Relative relief	3
6	Drainage	2
7	Aspect	1

The Landslide Susceptibility Zonation map with five different zones based on the degree of susceptibility show below:

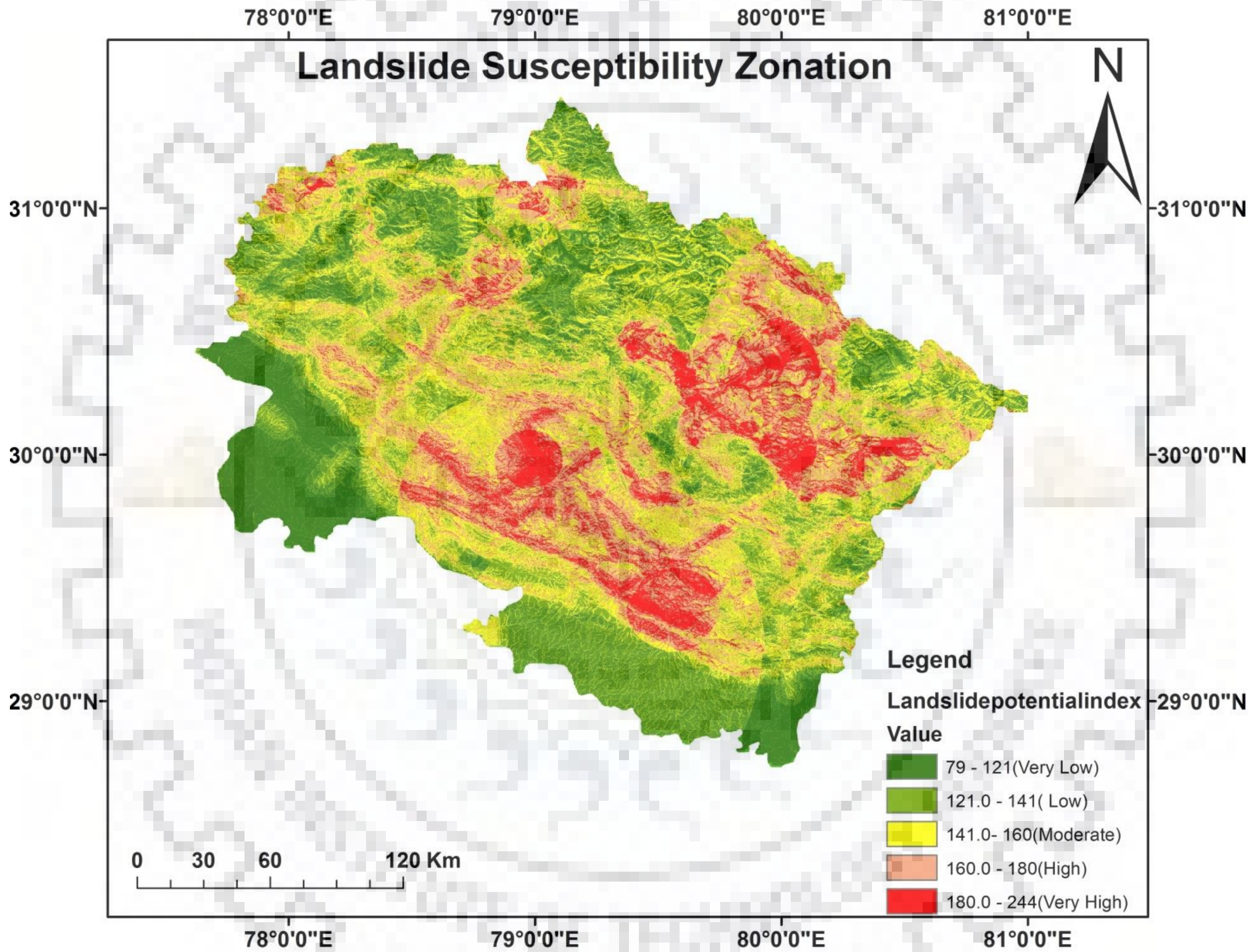


Figure 4.10: Landslide Susceptibility Zonation (LSZ) map.

Various Landslide Potential Index values (LPI) and their susceptibility of the study area are shown in below table (4.9)

Table 4.9: (LPI) Landslide Potential Index values and their susceptibility of the Study area.

LPI Value	Susceptibility
79-121	Very Low
121-141	Low
141-160	Moderate
160-180	High
180-244	Very High

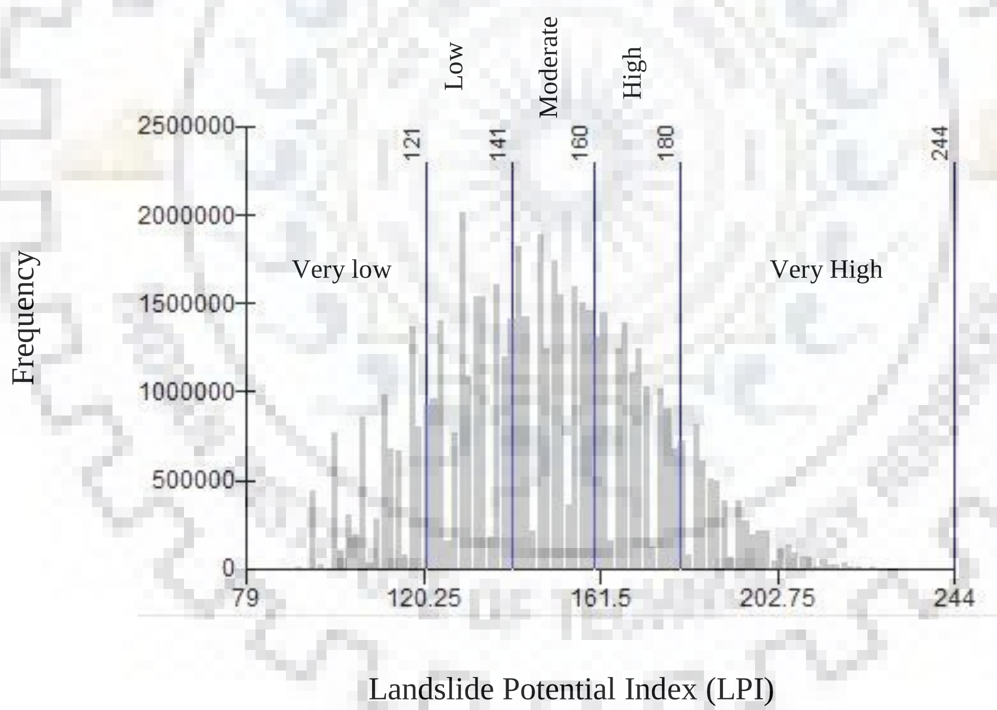


Figure 4.11: Graph between LPI (Landslide Potential Index)

vs

LDF (Landslide distribution frequency)

4.4 Map Validation:

This process explains whether the data and result acquired is accurate. After a complex trails data run the Final Landslide Susceptibility Zonation map (LSZ) is prepared and the existing historical landslides data acquired from Google earth is superimposed over the LSZ map. Based on the LSZ map, Landslide potential index (LPI) values vary from(79 to 244) which represents each area have a different degree of susceptibility such Very low, low, moderate, high, Very high. Based on the causative factors used for this study, down towards the southern part of the study area display a very low degree of susceptibility compared to the above region in the study area. The uppermost part of the study area is having high degree of susceptibility due to a high level of slope angle ranging from (45°-89.5°) and high altitude (> 3000 m) , high percentage of drainage coverage, the past seismicity activities such as the Chamoli earthquake (magnitude-6.6 1999) ,Uttarkashi earthquake (magnitude- 6.8 1991) causes seismicity induced landslides , the thrusts and lineaments such as three major thrusts lying MCT (Main central Thrust) passing through greater Himalayas,MBT(Main Boundary Thrust) Passing through lower Himalayas, MFT (Main Frontal Thrust) passing through the lowest part of Himalayas and Thrust NAT, Thrust SAT ,Thrust Ramgarh , which can generate the earthquakes. As discussed in section 5.3.6, the forthcoming seismic risk should be recognized for assessing landslide hazards in the hilly region, especially high prone Uttarakhand region. The high seismicity can not only trigger the earthquakes but they can activate old landslides and trigger new landslides. The landslide inventory data collected also validate that landslide occurs in the terrain regions such as the uppermost part of the study area. (Landslide Susceptibility Zonation) LSZ map with the historical landslides superimposed is shown below figure (4.12)

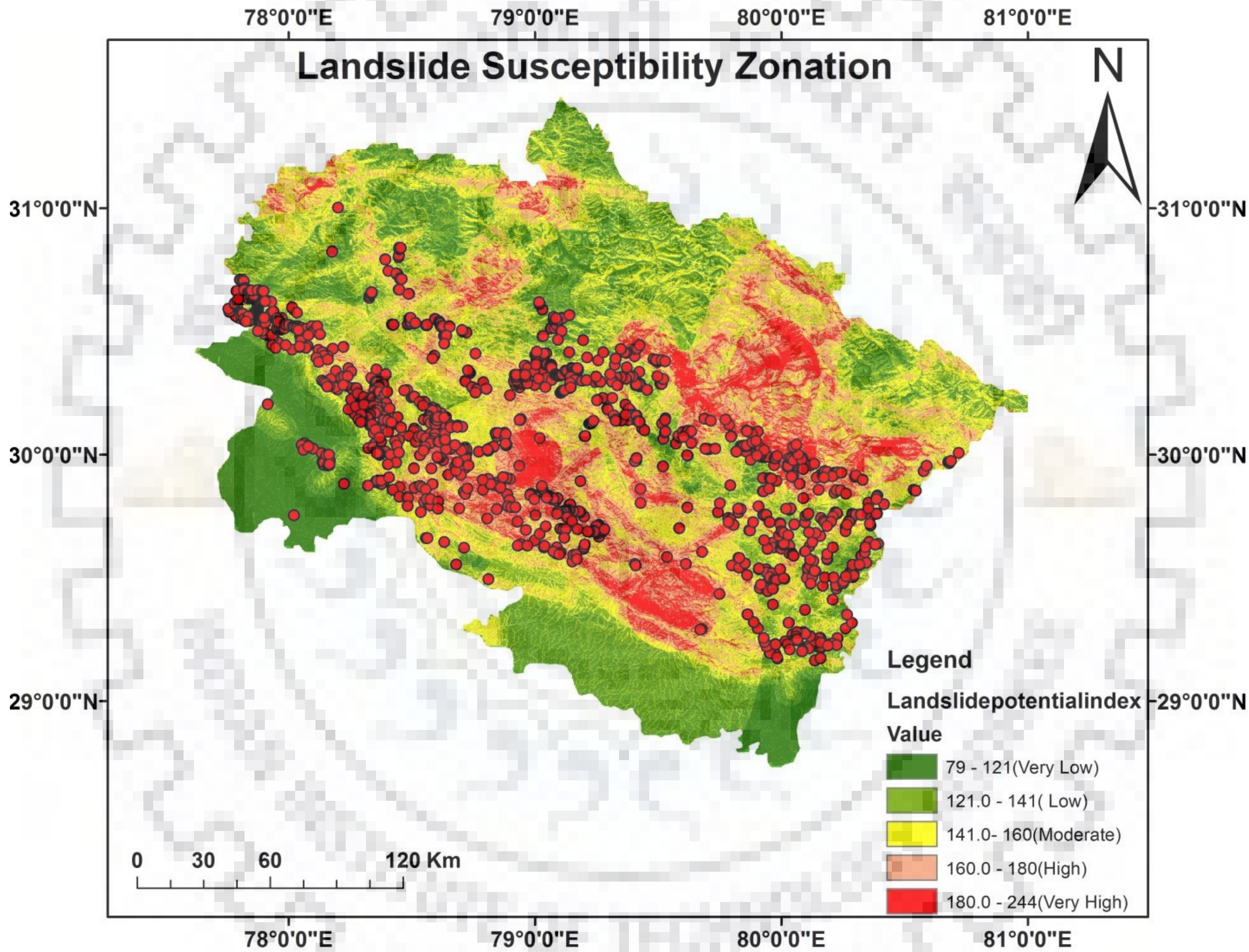


Figure 4.12: Landslide Susceptibility Zonation map (LSZ) with landslides superimposed.

Chapter 5 CONCLUSIONS AND FUTURE SCOPE

5.1 Conclusions:

This dissertation assimilates an all-inclusive study on estimating the landslide hazard for the state of Uttarakhand. Different causative factors such as Slope angle, Aspect, Relative Relief, Drainage, Lithology, Thrusts and Lineaments, Earthquake have been studied in detailed where special observation is made over the local seismicity in terms of earthquake data and thrusts and lineaments for the Landslide Susceptibility Zonation map (LSZ). A detailed landslide inventory data from Google earth providing the spatial distribution of landslides covering over the study area is prepared using ArcGIS. The preparation of thematic layers using the GDEM and the maps collected from the studies based on the factors affecting the occurrence of the landslides. Where the additional analysis is done to assign weightage and ranks to different causative factors based on their effect on landslides and using their classes for the calculation of Landslide Potential Index (LPI) of the study area. The Landslide Susceptibility Zonation map (LSZ) is prepared and classified into five different zones based on the degree of the susceptibility ranging from very low to very high.

These are conclusions after a detailed study and evaluation of the study area:

- The slope angle has a very well defined effect on (LSZ) Landslide Susceptibility Zonation map. The present study area having the slope angle range varies from (0° -89°), where more area is covered with angle above 30° hence it has more susceptibility.
- Aspect angle is the analysis of slope stability, where it is one of the controlling factors of the climatic condition of a specific area. The aspect angle is referred to as the direction of maximum slope of the terrain surface.
- The relative relief is directly proportional to the probability of slope failure due to the great momentum generated, hence its effect the occurrence of landslides.
- Drainage system which is also directly linked to the slope failure in the study area and have a huge influence on the occurrence of landslides.
- Lithology is having a dominant part on the landslide occurrences. According to the landslides distribution over the lithology map we can observe most of the landslides occurred on the area having the phyllite and quartzite rock formations in the study area.

Hence the upper Himalayan region is less susceptible compared to central region of the study area.

- Where local seismicity play key role for landslide occurrence, in terms of this dissertation, the present area has lot of local seismic activity hence it is included for the preparation of Landslide Susceptibility Zonation (LSZ) maps. We consider the earthquake data of past historical earthquakes along with the active faults, thrusts and lineaments for the preparation of the Landslide Susceptibility Zonation map (LSZ). These provide a future scope about the probability of seismically induced landslides.

5.2 Future Scope:

The methodology used for the prepared the preparation of Landslide Susceptibility Mapping of the present study area using software's like ArcGIS and remote sensing techniques using qualitative approach, which depends on map combination method, but there are different methods and software which can be used for the calculation of Landslide Susceptibility Mapping. Hence a further investigation is needed in order to optimize methodology and to acquire better results. The following issues can be taken for future research:

- Usage of high resolution remote sensing techniques in order to identify and mapping the debris flow in the study area to express the severity of flow, which can help to identify the highly susceptible zones.
- The causative factors for the occurrence the landslides such as soil type, land use-land cover (LULC), roads, rainfall can be used for the further studies .These needed a detail study due to the huge datasets which required great deal time to acquire. These parameters can provide a more in detail Landslide Susceptibility Mapping.
- More number of observation stations should be installed in complex terrain regions to monitor the causative factors details which can be useful to develop an early warning system for the future cataclysmic events.

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