EARTHQUAKE-INDUCED LANDSLIDE HAZARD ASSESSMENT OF UTTARKASHI DISTRICT, USING MULTI CRITERIA DECISION MAKING (MCDM) TECHNIQUE

A DISSERTATION

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IN

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Submitted by

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I, ASHI DWIVEDI, Roll No's – 2K21/GTE/21 student of M.Tech (Geotechnical engineering), hereby declare that the project Dissertation titled "Earthquake-induced landslide hazard assessment of uttarkashi district, using multiple criteria decision making (MCDM) techniques" which is submitted by me to the Department of Civil Engineering, Delhi Technological University, Delhi in partial fulfilment of the requirement for the award of degree of Master of Technology, is original and not copied from any source without proper citation. This work has not previously formed the basis for the award of any Degree, Diploma Associateship, Fellowship or other similar title or recognition.

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CERTIFICATE

I hereby certify that the Project Dissertation titled "Earthquake-induced landslide hazard assessment of uttarkashi district, using multiple criteria decision making (mcdm) techniques" which is submitted by Ashi Dwivedi, Roll No. – 2K21/GTE/21 here, Geotechnical engineering, Delhi Technological University, Delhi in partial fulfilment of the requirement for the award of the degree of Master of Technology, is a record of the project work carried out by the student under my supervision. To the best of my knowledge this work has not been submitted in part or full for any Degree or Diploma to this University or elsewhere.

Place: Delhi **PROF. RAJU SARKAR**

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ABSTRACT

Earthquake has played a major role in the current landslide scenario of Uttarkashi in the past few decades. Moreover, Uttarkashi lies in the seismically active part of India i.e. the seismic zone IV and V as per the Indian seismic zonation map IS 1893(Part 1): 2002. Hence it has become necessary to determine the landslides induced by earthquake with increasing magnitude and area of the earthquake. The main aim of this research is to prepare an earthquake-induced landslide susceptibility map using Analytical Hierarchal Process (AHP) and Relative frequency ratio (RFR) for Uttarkashi district, Uttarakhand. Over 65 Earthquake epicenters (ranging from a magnitude of 3.5 to 6.8) along with landslide points in and around the study area have been considered. Further, 11 factors are taken into consideration including tectonic framework, earthquake magnitude distribution, fault mechanism, topography along with other landslide factors. The consistency ratio (CR) determined for AHP is 0.075(<0.1), which indicates an acceptable preference matrix for the associated factors. The weights assigned to AHP for the above factors are validated using the RFR method. Earthquake-induced landslide susceptibility map is prepared, and the zones are classified accordingly. These maps were then validated by the area under the curve (AUC) method.

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CHAPTER 1 – INTRODUCTION

1.1 BACKGROUND AND MOTIVATION

Earthquakes have played a major role in the present landslide scenario of Uttarkashi for the past few decades. Earthquake induced landslides are a major geotechnical hazard and affect a major portion of landmass as well as population. Moreover, Uttarkashi lies in the seismically active part of India i.e., the seismic zone IV and V as per Indian seismic zonation map IS 1893(Part 1): 2002. Some of the major earthquakes include the 1991 Uttarkashi earthquake (also known as the Garhwal earthquake) with a moment magnitude of 6.8 Chamoli Earthquake 1999 measuring 6.8 on the Richter scale due to which, many landslides got induced and reactivated.[1] Hence it has become necessary to determine the Earthquake induced landslide hazard with increasing magnitude and area of earthquake. To avoid any type of fatal damage due to earthquake-induced landslides in future, it is required to formulate such methods that are not only practical in nature but also efficient for complete assessment of threat and zonation considering current scenario implementing damage reduction strategy. Earthquake-induced landslides act as frequent source of threat to people and property due to its extent. Natural phenomena called landslides reorganize the Earth's surface by moving mass from higher altitudes to lower ones.[2] Additionally, they endanger both people and infrastructure. Landslip processes have been extensively studied by physical scientists and engineers, in part to improve recommendations for lowering landslip risk. Even though the additional scientific understanding they have contributed makes it possible to more accurately anticipate the frequency, amplitude, and potential physical effects of various types of landslides, this kind of work is insufficient on its own to lower risk. Instead, it must be combined with social science research on the dynamic aspects of social systems. Hazard analysis must specifically take susceptibility and coping mechanisms into account.[3]

Due to a 50 percent increase in world population, an increase in the number of people residing in landslide-prone locations, and a warmer and locally wetter climate, the risk of landslides is anticipated to rise during the rest of the twenty-first century. By employing better scientific understanding of landslides in land-use decisions and by putting in place specific engineering mitigation measures to safeguard people and property, these realities can be partially mitigated.[4] The need to lessen danger to the most vulnerable communities through social justice based on a more equitable distribution of resources, however, is more fundamental.[5]

1.2 AIM OF THE PROJECT

Main fields of earthquake-induced landslides:

i. Scrutinize previous and latest landslides induced by earthquake
ii. Prognosis of potential earthquake-induced landslides
iii. Precautionary measures for landslides induced by earthquake, along with hazard map which can utilize to develop an early warning system.

In this study Analytical Hierarchy Process (AHP) based with GIS along with Frequency ratio models are used in mapping the landslides induced by earthquake. Landslide and earthquake triggering factors were evaluated by AHP and FR models, and both models displayed areas that were susceptible to landslides along with the extent of contribution of the causative factors on landslides.

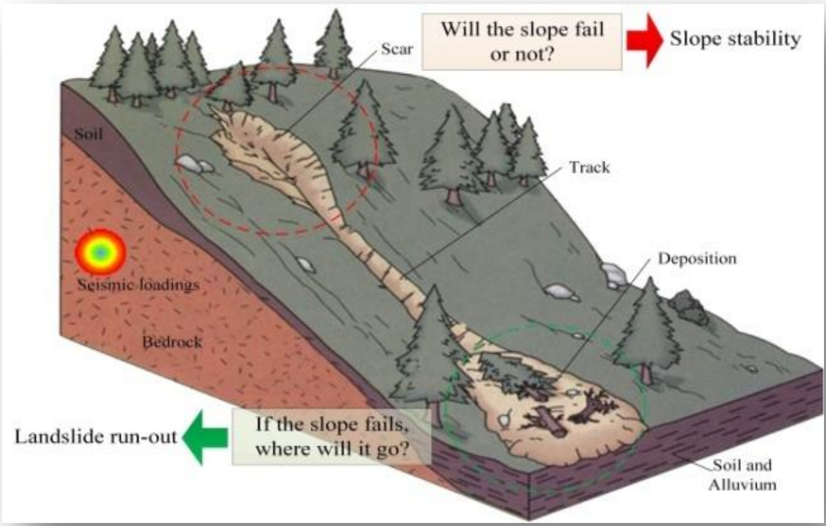


Fig.1.1.Stability and run-out analysis of earthquake-induced landslides

1.3 OBJECTIVE STATEMENT

i. To prepare earthquake induced landslide susceptibility map of Uttarkashi district (Uttarakhand) by using RFR method

ii. To produce landslide (earthquake induced) vulnerability map of Uttarkashi district (Uttarakhand) by inculcating GIS techniques along with AHP method

iii. PGA and PGV analysis of major earthquake occurring in the study area

iv. Preparation of resultant hazard maps, its analysis and comparison.

CHAPTER 2 - LITERATURE REVIEW

2.1. OVERVIEW OF PREVIOUS RESEARCH WORKS

Research works conducted previously and studies that have been conducted on earthquake induced landslides at various locations using various methods' have been tabulated in detail below. (Table 2.1)

Table 2.1.Literature survey

S.No.	Author	Study area	Methodology	Discussion
1.	Spyridon Mavroulis, et.al.(2022)	Cephalonia, Central Ionian Islands	Analytic Hierarchy Process (AHP) along with GIS	67 landslide inventory from 11 earthquakes that happened between 1636-2014 are included in the context of this investigation. Given this data, the study goes on to explore the ETL susceptibility using 10 landslip cause factors within the framework of an AHP. The sites of ETL on the island were more strongly correlated with four variables: slope, PGA, tectonic structures, and lithology. The accuracy of the landslip susceptibility evaluation is revealed to be fair to good and the AUC values of 80.3%, which also show that the influence of the researched factors to the cause of ETL was successfully identified.[1]
2.	Chyi-Tyi Lee, et.al. (2008)	Central Western Taiwan	Discriminant analysis of multivariate statistics	This paper presents a statistical model that employs earthquake shaking intensity as a landslide causative factor. The findings demonstrate the ability to appropriately identify the extent of influence if

				landslides in the studied area and foresee their development in nearby areas.
3.	Penjani Hopkins Nyimbili (2018)	Kuḉukcȅkmece in Istanbul, Turkey	AHP,GIS, TOPSIS	The distance to epicentre , liquefaction, topography, soil classification and fault mechanism are the five key factors that have the most impact on how earthquakes affect the research region. The TOPSIS method and GIS were used to simulate these outputs and construct seismic hazard maps, and the weights of these variables were found using AHP. When the earthquake hazard maps produced by the AHP and TOPSIS models were examined, a high degree of consistency and correlation was found.[11]
4.	Zahrul Umar, et.al. (2014)	West Sumatra Province Padang Pariaman	Frequency Ratio(FR) and Logistic Regression(LR)	A landslip inventory map for LSM was compiled from 87 different landslip locations that were found in various sources. Topographic wetness index (TWI), curvature, river, geology, SPI, altitude, rainfall, soil texture, land use/cover (LULC), soil type, , slope, aspect, lineament, and peak ground acceleration (PGA) are the landslip conditioning elements. Four PGA of 7.5, 8, 8.6, and 9 were gathered, and the model was created using PGA 8. Finally, a method known as the (ROC) approach was used for the validation of above generated maps. The validation findings for the model created by PGA 8 showed success

				rate and prediction rates of 84% and 78%, respectively. The outcome demonstrated the method's reasonable efficacy for mapping earthquake-induced landslip vulnerability.[5]
5.	Anita Rawat, et.al. (2018)	Uttarkashi (Uttarkhand)	Artificial Neural Network (ANN)	For this investigation, employed fieldwork, satellite images, and topographical maps that were already available. The primary goal of the current work is to integrate the findings from our research in order to create a GIS application that can forecast a region's future susceptibility to landslides and the percentage that each element would contribute to that susceptibility. Training, testing, and validation of the ANN model are done. The layers obtained will next be evaluated based on their approved coefficient in the final model, leading to the completion of an overlay analysis.[27]
6.	Sangeeta, et.al.(2019)	Chamoli (Uttarkhand)	Relative Frequency Ratio Method(RFR)	This study's goal is to create a map of the Chamoli district in Uttarakhand's landslip risk due to earthquakes. After that, check and confirm with the current landslip database. To establish a connection between landslip occurrence and landslip triggering factors, the RFR approach is applied. The weighted linear combination of the weights of the components is used to calculate the landslip hazard index (LHI). As input geo-factors, five variables—slope curvature, aspect, slope angle, NDVI, and PGA—are analyzed. The landslip danger

				map was created by integrating the rating maps with (GIS). A final map of the likelihood of landslides is then made, with five categories: very low, low, moderate , high, and very high.[12]
7.	Jazouli, et.al. (2019)	Oum Er Rbia high basin (Morocco)	Analytical hierarchy process (AHP)	The goal of the current effort was to create a landslip susceptibility map utilising a spatial multicriteria method based on GIS. Slope angle, aspect, elevation, distance to drainage and road, distance to fault, lithology and land cover were the eight landslide-factors that were chosen for evaluation. Using the Analytic Hierarchy Method, weights are assigned to each component based on how much of an impact they have on landslides. The weighted overlay method was used to produce the landslip susceptibility map, which was then divided into five classes. As per the final evaluation 30.16% of the study area lies in the very low risk zone, 12.66% lies in the low risk zone, 25.75% lies n the moderate risk zone and 9.11% of the arealies in the very high risk zone. These maps were then validated using ROC curves that showed fair result 76.7%.[2]
8.	S. Elayaraja, et.al. (2015)	The Nilgiris district in the Tamilnadu (India)	Seismic hazard analyzed using deterministic approach, seismic displacement of	In this study, the 350 km study area around Nilgiris is used to determine the deterministic seismic hazard of that region. The reaction spectrum and peak ground acceleration (PGA) at bed rock level are assessed. After taking topography into

			slopes is determined by Newmark's method.	account, ground response analysis is performed at 7 sites in the Nilgiris using the one-dimensional equivalent linear approach and the SHAKE programme. Five of the seven sites evaluated have a moderate seismic landslip hazard, according to the results of Newmark's approach, while two sites (Coonoor and Ooty) have a high hazard.[14]
9.	Yacine Achour, et.al. (2017)	A road section on a highway in Constantine , Algeria	Analytic hierarchy process (AHP) and Information value (IV) process	Based on historical data, aerial photo interpretation, remote sensing photos, and comprehensive field surveys, the landslide inventory map, which contains a total of 29 single landslide locations, was produced. Lithology, slope gradient, slope aspect, separation from faults, land use, separation from streams, and geotechnical characteristics are some of the various landslip influencing elements taken into account in this study. The lithological units and distance from faults maps were taken from the local geological database, and a theme layer map was created for each geoenvironmental element using a Geographic Information System (GIS). The maps of the geotechnical parameters were created using the geotechnical information obtained from laboratory testing. Then, using a GIS environment, analysis of the correlations between the landslide-related parameters and the landslide incidents was performed. From the AUC validation curve the maps have a

				success rate of 77% and 66% for IV and AHP models, respectively. Hence the IV model proves to be more accurate than AHP.[7]
10.	Cristina Gordo, et.al. (2019)	Ribeira Grande Basin, on Fogo Volcano, Azores	Bivariate state-of-the-art statistical method (the Information Value)	A straightforward bivariate technique (the Information Value) was utilized to create susceptibility models for failure based on the morphometric comparison and characterization of two landslip inventories. Kappa statistics, success rates, prediction rates, and prediction rates were used to validate the landslip susceptibility models. The findings demonstrate that shallow slides in the study area produced by earthquakes and precipitation have various morphometric traits.
11.	Phukon, et.al. (2012)	Guwahati City, Assam (India)	Analytic Hierarchy Process (AHP) and Geographic Information System (GIS)	The goal of the current study is to create a map of Guwahati's landslip susceptibility utilising the AHP and GIS. As required by the AHP, five likely causal elements that caused the previous landslides are employed for pair-wise comparison and matrix formation. A map of the city of Guwahati's landslip susceptibility was created using the landslip susceptibility index (LSI) in a GIS context. According to the statistics, 83.01% of the study area falls in the low to very low susceptibility zone, 5.89% of the study area falls in the moderate susceptibility zone, and 11.1% of the study area falls in the high susceptibility zone.[16]

12.	Mohammad Onagh,et.al .(2012)	Section of Uttarkashi district (INDIA)	Multiple linear regression method *,	The following research focuses on the stability analysis that are conducted to construct a multiple linear regression map of landslip vulnerability by evaluating the strata. The Regression analysis considered distance to road, river fault, rainfall, landcover, lithology, slope and aspect factors as variables. Finally, an overlay analysis was performed by assessing the layers created in accordance with their final model's acceptable coefficient. The Area Under Curve (AUC) technique and historical landslip data were used to validate the outcome. The validation done using AUC displayed an optimum level of agreement of the landslide maps with evaluated data. As a result, the model's success rate (76.2%) demonstrates great forecast accuracy.[13]
13.	Bayes Ahmed(2014)	Chittagong Metropolitan Area, Bangladesh	AHP, WLC, and OWA	Producing the Landslide Susceptibility Maps for CMA is the main goal of this study in order to create effective landslide catastrophe risk mitigation measures. In this study, the landslip prone locations in CMA were scientifically assessed using three distinct methods that are: Multi-Criteria Decision Analysis methods incorporated with Weighted Linear Combination, Geographic Information System based: Artificial Hierarchy Process, and Ordered Weighted Average. There were nine distinct theme levels or landslip causative elements taken into

				account. The three weighted overlay techniques were then used to create seven different scenarios that were susceptible to landslides. Later, the area under the relative operating characteristic curves was used to validate the approaches' performances.[17]
14.	Lamek Na hayo, et.al. (2019)	Western province of Rwanda	Analytical hierarchy process (AHP) and Certain factor (CF) method	96 sites that were localized by field surveys were used to create a map of the land slides. normalised difference vegetation index Elevation, lithology, driving distance, , rainfall, soil texture, land use and cover and slope angles were the eight conditioning elements examined. CF model produced a higher accurace map of 74.62%
15.	Hawas Khan et.al.	Central Karakoram National Park (CKNP) Haramosh valley, Bagrote valley and parts of Nagar valley in the Gilgit-Baltistan, Pakistan	AHP, FR and GIS	The northern Pakistan is attributed with rough terrain, active seismicity, monsoon rains, and therefore hosts to variety of geohazards. Among the geohazards, landslides are the most frequent hazard. This study aims to develop a remote sensing based landslide inventory, analyzing their spatial distribution and develop the landslide susceptibility map. The SPOT-5 satellite image was used to develop a landslide inventory. The landslide causative factors of topographic attributes (slope and aspect), geology, landcover, distances from fault, road and streams were used to evaluate their influence on the spatial distribution of landslides. The study revealed that the

				distance to road, slope gradient has the significant influence on the spatial distribution of the landslides, followed by the geology. The derived results were used in the Frequency ratio technique to develop a landslide susceptibility map.

2.2. LANDSLIDE DEFINITION AND TYPES

A landslip is a downward movement of rock, soil, or both that occurs on the surface of a rupture, which can be curvy (rotational slide) or planar (translational slide). Much of the material often travels as a coherent or semi-coherent mass with minimal interior deformation. It should be remembered that landslides occasionally also entail other kinds of movement, either at the time of the failure or afterwards, if the properties of the displaced material change as it slides down-slope. [6] The numerous forms of landslides are described and illustrated in this section. Planning or adopting the proper mitigation measures to reduce the risk of loss and damage requires careful consideration of the features of the specific type of landslip hazard in your area. The type of landslip will define the expected volume of displacement, run-out distance, potential speed of movement, potential impacts of the landslip, and the relevant mitigating actions to be taken. [7]

According to the type of movement and the type of material involved, there are various types of landslides. In a nutshell, the components of a landslip mass can be either rock or soil (or both); the latter is referred to as debris if it is primarily made up of coarser fragments or earth if it is mostly made up of sand-sized or smaller particles. [8] Depending on the movement type—fall, topple, slide, spread, or flow—the landslip mass is really shifted internally. (Fig.2.1) Thus, two phrases (rock-fall, debris flow, etc.) that refer to material and movement, respectively, are used to characterize landslides. Landslides can also result in a multi-movement complicated failure (for example, a rock slide-debris flow). [9]

Falls: A fall starts when soil, rock, or both separate from a steep slope along a surface where there has been little to no shear displacement. Following that, the material generally descends by falling, bouncing, or rolling. [10]

Topple: A topple is the forward motion of a mass of soil or rock out of a slope around a point or axis below the displaced material's centre of gravity. Toppling can occasionally be accelerated by the weight of the material that is upslope from the displaced mass. In fractures in the bulk, water or ice can occasionally induce toppling. Topples can contain rock, debris (coarse material), or earth materials (fine-grained material). An elaborate and composite tumble is possible. [10-11]

Slides: A slide is a downward movement of a mass of soil or rock that occurs on ruptured surfaces or on relatively narrow zones of extreme shear strain. Moving material does not initially start moving simultaneously across the entire area that would eventually become the surface of rupture; instead, it starts expanding from a specific area of failure.

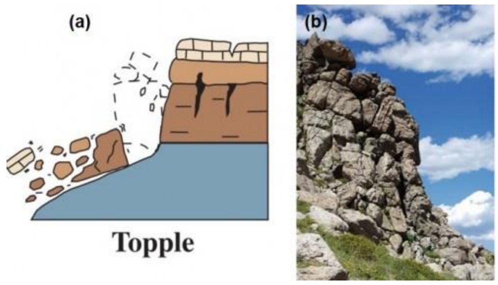
Spreads: A cohesive soil or rock mass that has expanded along with a general subsidence of the cohesive mass into softer underlying material undergoes spread type landslide. Spreads may be caused by the softer underlying material flowing or liquefying (and extruding). Block spreads, liquefaction spreads, and lateral spreads are a few different types of spreads.

Flows: A flow is a continuous motion of matter across space in which shear surfaces are ephemeral, closely spaced, and frequently not preserved. The displaced mass of a flow has component velocities that are comparable to those of a viscous fluid. There is frequently a gradual change from slides to flows, depending on the volume of water available, its mobility, and the direction of movement. [12]

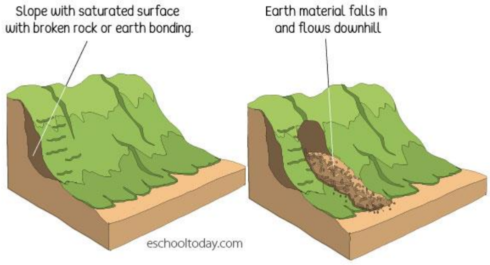
Debris Avalanche: Massive, highly quick, and frequently open-slope flows known as debris avalanches are produced when an unstable slope collapses. When the fragmented debris that results is swiftly pushed away from the slope, these flows are produced. Snow and ice may occasionally help with the movement if there is enough water, and the flow may turn into a debris flow or lahars.

Solifluction: Solifluction has an impact on slopes' saturated top layer. Due to the variation in temperature on daily as well as seasonal basis there is modifications in the water phase and water content of fine-grained soils in cold places, this is frequently a sluggish movement caused by the freeze-thaw process.

Rock fall



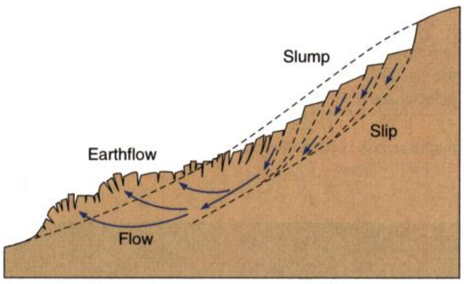
Topple



Flow

Debris slide

Solifluction



Cross section of a complex landslide characterized by slumping at the top and earthflow at the base.

Complex landslide

Fig.2.1.Various types of landslip movements

Table.2.2.Classification of types of landslip movement

		MATERIAL TYPE		
MOVEMENT TYPE		**ROCK**	**DEBRIS**	**EARTH**
	FALL	Rock-fall	Debris fall	Earth fall
	TOPPLE	Rock topple	Debris topple	Earth topple
	SLIDE	Rockslide	Debris slide	Earth slide
	SPREAD	Rock spread	Debris spread	Earth spread
	FLOW	Solifluction flow	Debris flow	Earth flow
	COMPLEX	Rock avalanche	Debris slide-debris flow	Earth slide- earth flow

2.3. LANDSLIDE SUSCEPTIBILITY MAPPING

A method for categorizing the slope into zones depending on the degree of actual or anticipated landslip susceptibility and hazard is known as landslip susceptibility or hazard zonation. A quick evaluation of slope stability over a sizable area requires consideration of landslip susceptibility and hazard zonation. [13] The spatial future incidence of landslides can be forecasted/ provided with vital information using a map of landslide susceptibility. A map of the potential for landslides, however, can predict where and when they will occur in the future.

A landslide susceptibility map is further applicable to planning, design, and risk analysis for both urban and rural areas. The various statistical methods are the weighted liner combination model (WLC) the logistic regression model, fuzzy synthetic evaluation model and neural network model . Various weighting methods like analytical hierarchy processes (AHP) which is considered as a decision-making method for analyzing multi-faceted decisions can be implemented in mapping landslide susceptibility of the study area. There are numerous methods that have been developed for landslip susceptibility and hazard mapping, and they can be divided into qualitative, semi-quantitative, and quantitative approaches. A map of landslip susceptibility categorizes areas into very low, low, moderate, high and very high susceptibility areas. The landslide susceptibility map considers where landslides happen as well as their causes, including slope, soil type, and the effect of local water flow. [14-20]

2.4. METHODS OF PREPARATION OF SUSCEPTIBILITY MAP

Different techniques, scales, and evaluation criteria have been used to build a variety of landslip susceptibility mapping (LSM) models, ranging from knowledge-driven to process- and statistical-based models. In terms of the readability and usability of the output maps, the most popular and successful methods rely on more or less sophisticated mathematical and statistical techniques, such as (for a thorough and current review) logistic regression, neural network analysis, data overlay, index-based, and weight of evidence analyses, as well as machine learning.[21] They need a thorough process for calibrating and validating the models, as well as an a priori characterization of the landslip inventory and predisposing factors.

However, due to the intricacy of the elaboration process, it is frequently impossible or at least challenging to reproduce these methods and apply them to various fields. The grid, which comes in matrix form, can be easily accessed in GIS, and is straightforward to handle for data processing, is the most common mapping unit for LSM.[22] Grid cells, however, are not connected to geological-geomorphological contexts since they are unable to depict the physiographic characteristics of the terrain. Unique condition units (UCUs), homogeneous regions with morphodynamically limited spatial constraints; make up a more representative segmentation technique. They better approximate the morphodynamic reaction of the slope to the occurrence of landslides by maximising the internal homogeneity and the outward heterogeneity of the specified parameters. [23] Geomorphological features, such as slope units (SUs), which are generated by dividing subcatchments into two halves and taking the slope gradient and aspect into account, form the basis of a particularly effective segmentation technique. This type of terrain segmentation has been shown to be effective in some experiments, even outperforming grid-based models. The resultant landslip susceptibility maps are more readable and directly related to the terrain structure, which is one of the key benefits of SU segmentation.[24]

Numerous scientific studies have been conducted on the subject of landslip susceptibility, many of which use an exclusively statistical approach and compare multiple techniques on the same dataset without discussing the significance of the predictive relationships or how they relate to morphodynamic models. The models must be converted into forecast maps so that administrators can utilise them as a reliable tool for risk management.

i. Landslide inventory method: A straightforward procedure known as inventory captures the location and scope of events that took place in a certain area. The method used to record the location, magnitude, time of occurrence, displaced material, and types of slope collapse is known as a landslip inventory. [25] The position and volume of a landslip are all that are shown by this method, which has been used as the foundation for assessments of landslip susceptibility, hazard, and risk. However, it does not indicate the spatial relationship between a landslip and sets of landslip components. This method uses field mapping, historical records, satellite image analysis or Google Earth Imagery, and aerial photograph interpretation to gather data about landslides.
ii. Qualitative method: The expert evaluation method, however extensively utilized, is a somewhat subjective methodology that describes the severity of the landslip condition based on the expert's judgment. Qualitative approaches are an expert-driven approach that calls for specialists with relevant experience. The primary activities for assessing landslip susceptibility and hazard are field geomorphological analysis, landslip inventory analysis, and parameter assignment superimposition. The disadvantage of these approaches is their reliance on subjectivity and the expertise and professional background knowledge of specialists. Heuristic, landslide inventory mapping, landslide hazard evaluation factor, and slope stability evaluation parameter have all been incorporated into this method.[26]
iii. Bivariate statistical analysis: The bivariate statistical method, which can distinguish the effects of each sub-factor class for landslip occurrence, is simple to use and up-to-date. The characteristics that improved the likelihood of the landslip occurring have been considered as the independent variable in the bivariate statistical technique because the presence of the landslip has been considered as the variable.[27] Each determinant map in this method has been broken down into sub-classes to determine how each class of factor will react when a landslip occurs. The weighting values supported the landslide densities of each determinant class, along with the landslide factor classes, are frequently paired with a map of the distribution of landslides. The weighted raster map is carefully added up using a raster calculator

in Math algebra under the GIS tool to urge the landslip susceptibility index map after weight value calculation.

To create the ultimate landslip susceptibility map, the landslip susceptibility or hazard index map is frequently reclassified using several techniques including natural break under the GIS tool. Bivariate statistical approaches have the advantages of covering a large region at a reasonable cost, being easy to use, and having the ability to offer spatially dispersed landslide information and its interaction with landslide factors. However, the following constraint applies to bivariate statistical methods: 1. It is unable to differentiate between factors that are more influential and less influential. 2. It cannot provide information about the material's inherent conditions, unlike geotechnical methods. 3. It can identify areas that are susceptible to landslides, but it cannot predict when they will happen. Landslides must occur in one area for it to be possible to anticipate the opposite area, which is affected by environmental factors. The most prevalent methods used in bivariate statistical analysis include the weight of the evidence, information value, certainty factor, and frequency ratio.[27]

iv. Data mining method: Modern data mining techniques, such as random forest boosted regression trees, classification and regression trees, Naive Bayes, support vector machines, kernel LR, logistic model trees, index of entropy, and artificial neural networks, have become widely used in landslip susceptibility modeling. Because data mining techniques require large computing resources and a lot of time, they are unable to calculate the effects of each landslip factor class.[28] As a result, their internal calculations are complex and difficult to understand. Although the level of predicted accuracy for statistical and data mining methods differs only slightly, both may provide accurate and reliable landslip susceptibility maps for hazard mapping.

v. Landslide risk mapping approaches: The projected loss or damage resulting from landslip incidents, such as fatalities, damage to buildings, infrastructure, farming, and the environment, as well as the disruption of services and economic activity, is known as landslip risk. Landslip risk mapping is less popular than landslip susceptibility and hazard mapping because it requires more complicated input parameters. [29] Due to the absence of information required to develop input parameters such as vulnerability/susceptibility, hazard, and element at risk, it is a difficult process.

The regulation of land use, landslide risk management, and mitigation techniques all heavily rely on landslide risk maps in addition to landslide susceptibility/vulnerability and hazard maps. Estimating landslip susceptibility, hazard, and element at risk is required when creating a landslip risk map. Qualitative and quantitative methodologies are frequently used in landslip risk mapping. When the numerical evaluation of hazard, vulnerability, and element at risk is challenging due to a lack of landslip frequency, date of occurrence, and magnitude data, the qualitative (heuristic) method is used to estimate the amount of risk in a region qualitatively. [30] A mathematical equation can be used to quantitatively estimate the landslip risk. Hazard + vulnerability + element at risk = risk, where the risk is the likelihood that a specific type and degree of landslip will occur in a specific area during a given time frame. The level of expected loss as a result of landslides is called vulnerability. Elements in landslide-prone locations that could be impacted are the elements at risk.

vi. Semi quantitative method: The impacts of landslip factors on landslip incidence are graded and weighted using semi-quantitative methods, which combine qualitative and quantitative methodologies. This approach allows for the evaluation of the influence of landslip governing elements on landslip occurrence using both qualitative and quantitative methodologies. Examples of semi-quantitative techniques include the analytical hierarchy process, weighted linear combination, and expert knowledge/heuristic. Although this method includes some statistical principles, considerable subjectivity still exists because it is based on the expertise and background of the expert.

vii. Physical based approach: Numerical models using finite elements and limit equilibria are included in the physical-based approach. These techniques can be used to analyze the stability of both rock and soil slopes. With the use of this method, we can immediately employ quantitative data that show hazards in terms of their absolute value, factor of safety, or probability. The quantitative value of the inherent slope materials of the factor of safety over a specified area is determined using physical-based methods. These techniques can be used when the intrinsic qualities of the slope material are uniform and the landslide types are straightforward (shallow landslides). [31] It needs specific ground information, including slope angle, pore water pressure, depth below the terrain's surface, slope height, soil unit weight, soil strength, and soil layer thickness. The physical-based approach has only been used in a restricted area, and its shortcomings include simplicity and the inability to obtain data often. These techniques can be used to conduct an on-site investigation to determine the geotechnical characteristics of the soil/rock, soil depth, surface and subsurface water conditions, slope geometry, landslip location, failure mechanism, depth, and distance from the landside. [32] By computing safety factors with various tools, such as PLAXIS and Slope/w in the GeoStudio software package as two- or three-dimensional models, these techniques are used to analyze slope situations.

viii. Quantitative (statistical) method: The statistical approaches are indirect procedures that are frequently or consistently used to evaluate the relationship between mathematically based landslides and their governing variables. Both multivariate and bivariate statistical procedures fall under this category. [33] Reliable results are produced through statistical approaches. In contrast to the qualitative method, the numerical methods, which rely more on the mathematical model, expression, and less on expert judgement, produce findings that are more consistently accurate. The statistical approach is one of the quantitative techniques used to assess the geographical slope instability based on the association between past/current landslides and landslip variables. An indirect method that is regarded objective and works by integrating a GIS tool with statistical analysis based on the spatial relationship between the landslide and sets of landslide components is the use of statistics to create a landslide hazard/susceptibility map.

The most challenging aspect of this strategy, however, is the iterative model calibration, model validation, and precise database creation processes. The statistical method's drawback is that it takes a long time to collect comprehensive, high-quality data on landslides and landslide factors over a wide area. Where there hasn't been a landslip, the statistical technique is inapplicable. One of the drawbacks of statistical techniques for mapping landslip susceptibility, hazard, and risk is this. [34]

ix. Multivariate statistical analysis: Results from this strategy will be more accurate and realistic. In contrast to bivariate statistical approaches, it additionally takes into account the interactions between landslip components. The relative importance of each cause to the level of risk in a specific land unit is shown by the causal factors' weight. Unlike the bivariate statistical technique, the multivariate statistical procedure aids in multivariate statistical analysis.[35] The ability to determine the degree to which specific landslip factors have an impact on the likelihood of a given landslip is one of the advantages of the multivariate method. The most widely used techniques in this methodology are cluster analysis, discriminant analysis, and logistic regression.

x. Heuristic method: This method, which is based on opinion, categorises landslide susceptibility and hazard maps by mapping all contributing elements to landslides and properly classifying each contributing factor. This method's shortcomings include its subjectivity.

xi. Slope stability evaluation parameters (SSEP): In order to create a landslip susceptibility map, slope stability evaluation parameters (SSEP), a technique for assessing landslip hazards, are used to assess both internal such as material of slope, its geometry, discontinuities and ground water conditions along with external factors such as rainfall, earthquake magnitude and other anthropogenic activities. This method takes into account the causal factors for both dynamic and static landslides. Although this method is straightforward and backed by a wealth of field data, weighting assignment is subject to interpretation.

xii. Landslide Hazard evaluation factors (LHEF): Using solely the inherent regulating elements, Anbalagan claims that this method is useful for landslip susceptibility and hazard zonation/mapping. Over a sizable area, it is easy and affordable. However, this approach has the following drawbacks. has a low value rating for the impact of groundwater on slope instability. The triggering variables are not taken into account. The state of the rock mass with the structural discontinuity and its properties (roughness, aperture, etc.) are not taken into account. It is arbitrary. Give both structural discontinuity and lithology the same rating, but structural discontinuities have a greater impact. [36]

CHAPTER 3 - STUDY AREA

3.1 UTTARAKHAND

Uttarakhand has a total of 13 districts divided into two sections that are, the Garhwal section and the Kumaon. The landscape of the Garhwal Himalaya is largely fragile in nature and prone to various geological casualities which includes landslides as a regular. Situated in the northern part of India, the state of Uttarakhand shares its boundaries in the north with China and with Nepal in the. (Fig.3.1) Uttarakhand has an area of 53,483 Km^2 and lies between 28°43' N to 31°27' N latitude and 77°34' E to 81°02' E longitude. [37] It has a forest area of approximately 34,651 Km^2, which maks upto 64.79 % of its total geographical area covered by the state. There's a great variation in climate and vegetation of the region due to its nearness to the Himalayas, ranging from the glaciers at the highest elevations to tropical forests at the lower elevations. Major forest types that can be seen here include Sub Tropical Pine, Tropical Moist Deciduous, Himalayan Moist temperate, Tropical Dry Deciduous, Himalayan Dry Temperate. The average rainfall in the state is 1550 mm.

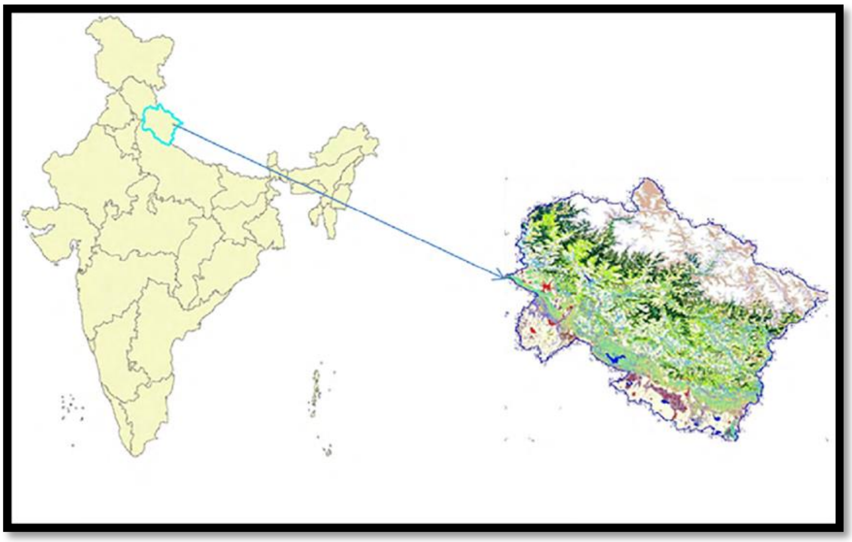


Fig.3.1. Study area map showing Kangra, Himachal Pradesh and India

3.2 UTTARKASHI

Uttarkashi lies along the upper Himalayas, containing various geographic features varying from green valley's to snow filled high peaks and glaciers. The topography also has a series of ridges and valleys. Each ridge is followed by another one forming long chains. Larger part of the topography is mountainous formed of high ridges and hills, where as plateaus and flat land are rare (https://uttarkashi.nic.in/about-district/). (Fig.3.2) The Annual average rainfall is around 1750 mm.

Also this area lies at the tow side of river Bhagirathi, suffering from frequent landslides every year. Between July and September, the region experiences significant rainfall, while between January and March, it experiences moderate rainfall. [38-39]

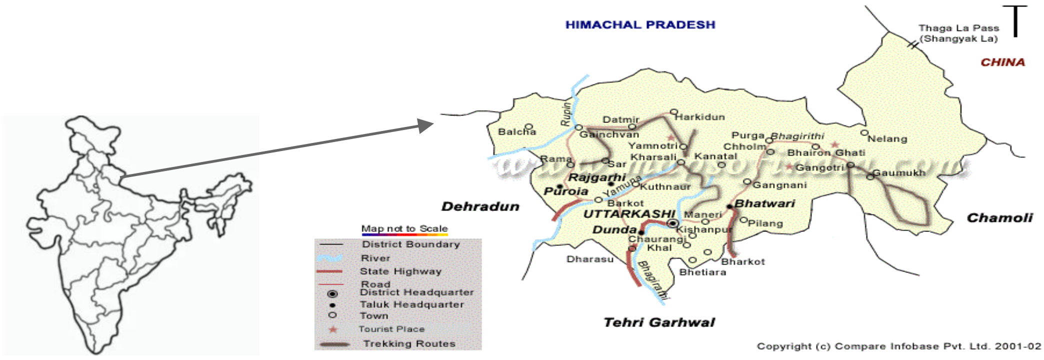


Fig.3.2.Study area- Uttarkashi, Uttarakhand INDIA

CHAPTER 4 - DATA PREPARATION

4.1 FACTORS AND THEIR SOURCES

For a good landslide prediction, the data used along with the respective source must be reliable and accessible. Preparation of thematic data maps is done using below mentioned sources. (Table.4.1) The base map of India and the corresponding Uttarkashi district has been taken from Advances in Geographical Research. The cell size of these maps is adjusted to 30x30. Besides, all the maps have the same Projected Coordinate System i.e., WGS 1984 UTM Zone 43N. All landslide and earthquake causative factors were regrouped into suitable number of classes before further analysis. [40]

Table.4.1.Data description and their respective sources

S. No	DATA	Type	DESCRIPTON	DATA SOURCE
1.	Landslide inventory map	POINT	693 landslide points considered in and around Uttarkashi	Bhukosh Portal, Geological Survey of India.
2.	Elevation	DEM(RASTER)	Derived from digital elevation map file SRTM using ArcGIS	Open Topography, SRTM GLI Global
3.	Slope	DEM(RASTER)	Derived from digital elevation map file SRTM using ArcGIS	Open Topography, SRTM GLI Global
4.	Aspect	DEM(RASTER)	Derived from digital elevation map file SRTM using ArcGIS	Open Topography, SRTM GLI Global
5.	Curvature	DEM(RASTER)	Derived from digital elevation map file SRTM using ArcGIS	Open Topography, SRTM GLI Global
6.	Distance from roads	LINE	Polyline type shape files have been used to determine the distance	Bhukosh geoportal, Geological Survey of India.
7.	Distance from River	LINE	Polyline type shape files have been used to determine the distance	Bhukosh geoportal, Geological Survey of India.
8.	Tectonic framework	POLYGON	Helps to determine the earthquake prone areas	Bhukosh geoportal, Geological Survey of India.
9.	Earthquake magnitude distribution	POINTS	Over 65 earthquake points have been considered	Bhukosh geoportal, Geological Survey of India.

10.	Lithology	POLYGON		Bhukosh geoportal, Geological Survey of India.
11.	Fault mechanism	LINE	Important factor for understanding the earthquake mechanism	Bhukosh geoportal, Geological Survey of India.
12.	LULC	POLYGON	LULC map is an important causative factor that has major and direct effect on landslide occurrence.	

4.2 ROLE OF VARIOUS THEMATIC LAYER FACTORS

Following are the thematic maps displaying the geological, morphological and seismological triggering factors tht have been considered for the landslide susceptibility calculations.

4.2.1 SLOPE

A landslide's likelihood is primarily determined by the slope. Landslides typically occur in areas with very high slope values. One crucial component of landslip stability is the s lope angle. It runs from 0º to 90º, with 0° standing for flat terrain and 90° for vertical on es. In the research area, slope values range from 0° to 60°. There were five courses on th e study area's hill. The majority of the landslides, according to the theme map, happen at slope angles between 30º and 45º.(Table.6.5(a)) In general, the frequency of landslides rises with the slope grade until it reaches its maximum frequency, after which it starts to fall. Similar to Uttarkashi, the incidence of landslides rises with slope angle until the maximum is reached in the 30º-45º class, and then gradually falls. (Fig.4.1)

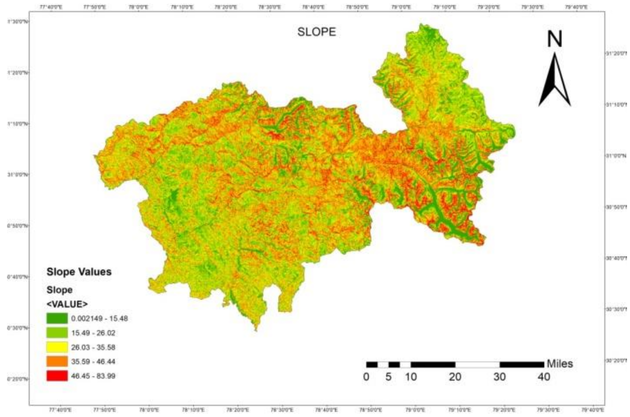


Fig.4.1.Slope gradient map

4.3.2 ASPECT

Aspect is a crucial component in creating landslip susceptibility maps, just like slope. A spect areas were divided into eight groups on the aspect map, including East, Southeast, South, Southwest, West, Northwest, North, and Northeast.(Table.6.5(b)) The slope's dir ection is referred to as an aspect. The slope aspect typically reflects the vegetation and the moisture holding capacity o the soil, which may affect the soil's strength and in turn, it's vulnerability to landslides. The majority of landslides, as shown by research, took place on the South, Southwest, and West side slopes. (Fig.4.2)

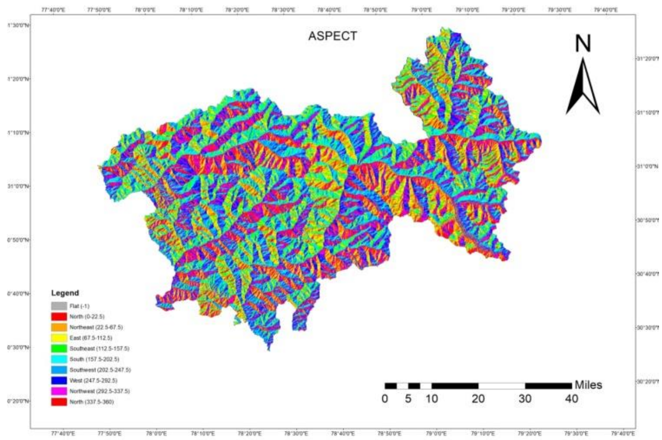


Fig.4.2.Slope aspect map

4.3.3 CURVATURE

Surface curvature at a place is the bend in the line created when the surface and a plane cross at this point, with the line having a particular direction. Positive and negative numbers indicate surfaces that are upwardly concave and convex, respectively, whereas zero values represent surfaces that are flat. The six classifications of the curvature map range from very convex (-10) to highly concave surface. (Table.6.5(c)) (Fig.4.3)

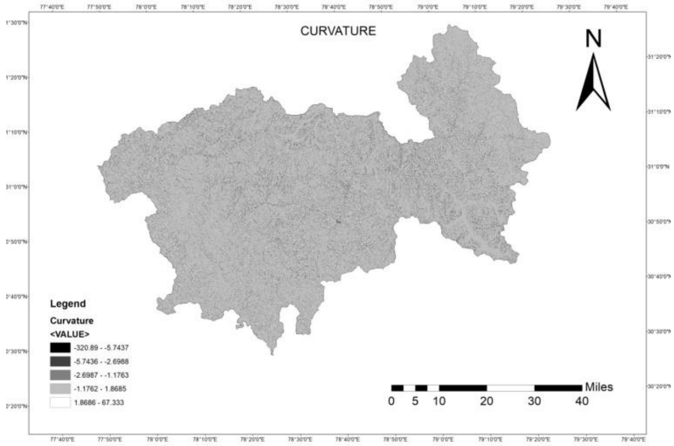


Fig.4.3.Curvature map

4.3.4 ELEVATION

The Elevation map was derived from digital elevation maps (DEM file) and the classification of this map was done using Natural Breaks (Jenks) method. Most of the landslides (over 55%) occur at an elevation of about 1500m-3000m. (Table.6.5 (d)) (Fig.4.4)

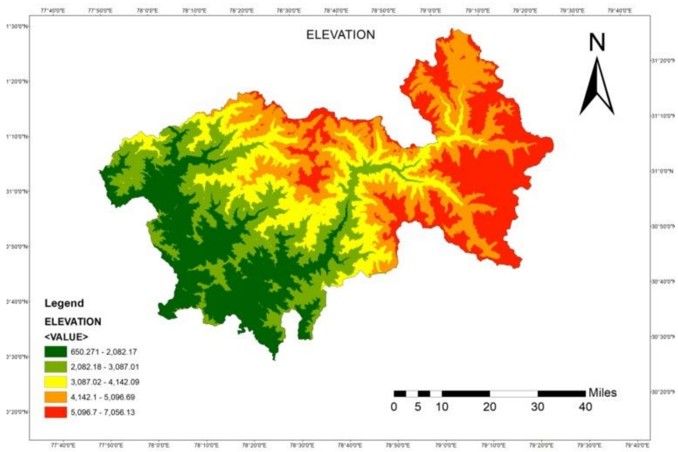


Fig.4.4.Elevation map

4.3.5 LITHOLOGY

Lithology is an important parameter affecting landslides because different litho logic units have different responses to active earthquakes and landslides (geomorphologic processes). Variation in lith ology often leads to a difference in the strength and permeability of rocks and soils. Hence these variations were grouped into (i) Stromatolitic limestone and slate (ii) Granite (iii) Gneiss, mica schist with marble band, (iv) Phyllite, quartz, shale, dolomite, tuff with dolerite, (v) Gravel, pebble, sand, silt and clay, etc.[14] (Table.6.5(e))(Fig.4.5)

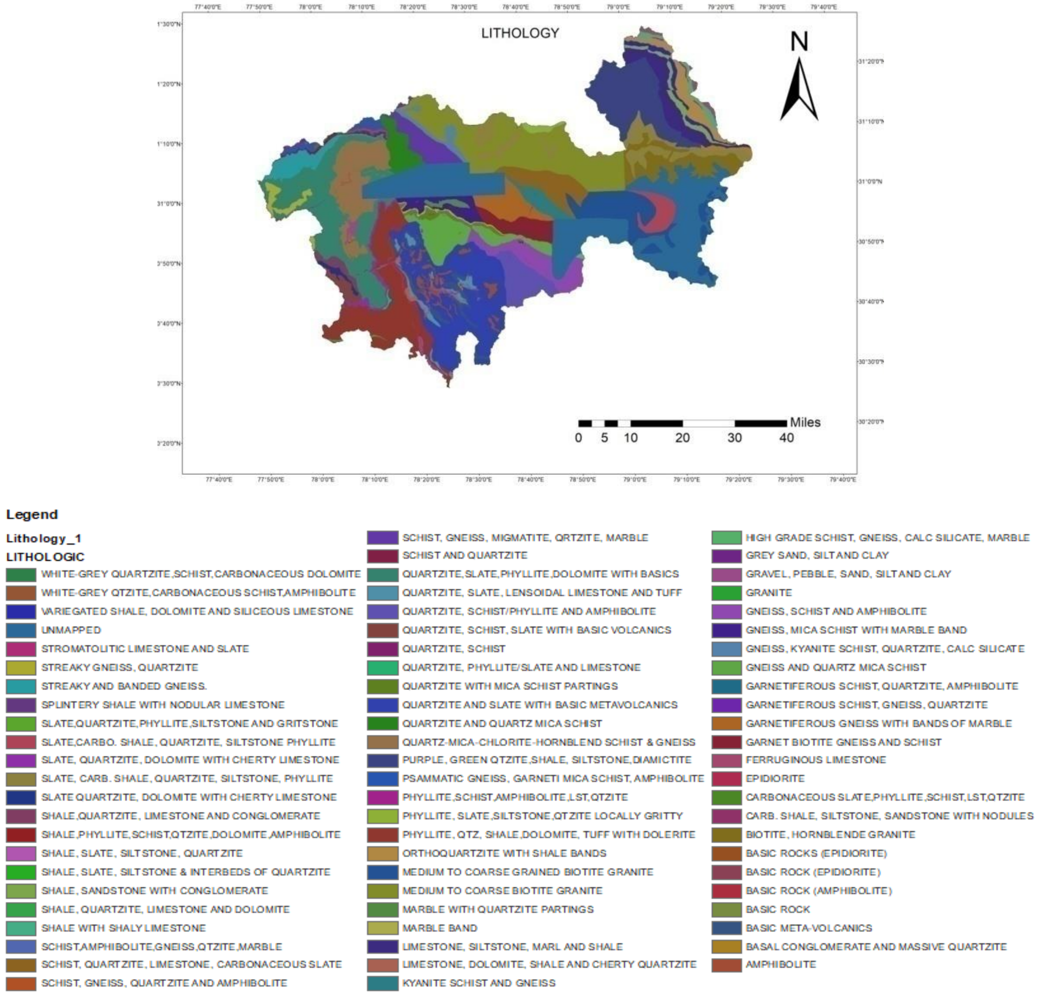


Fig.4.5.Lithology map

4.3.6 LULC

Barren lands are more susceptible to landslides whereas vegetative land control various factor in holding the land by preventing soil erosion and providing anchorage to it hence are less susceptible to landslides.[42] A major part of the study area is represented by trees and range land and the remainder is water, crops, built area, bare ground, and snow/ice. (Table.6.5(f))(Fig.4.6)

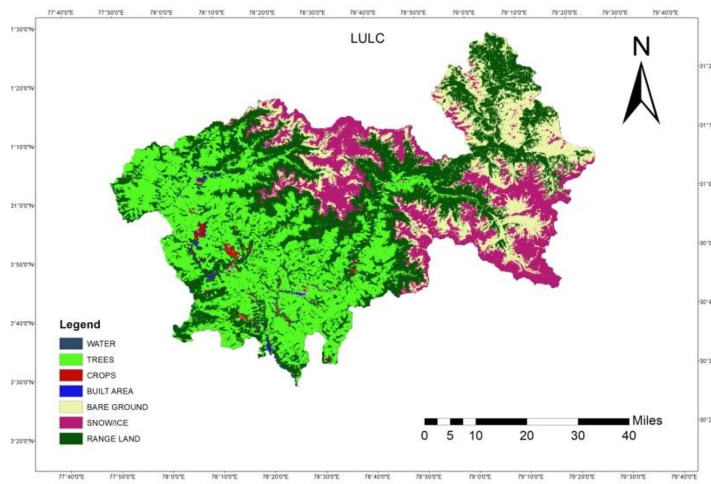


Fig.4.6. Land use map

4.3.7 TECTONIC FRAMEWORK

The Tectonic build of the study area helps us to analyze the various possible types of movements that may occur. This is largely responsible for both earthquake and landslide occurrence moreover, Uttarkashi lies on the boundary of the Indian and Eurasian tectonic plates. The tectonic framework of this location has been classified into the following classes- Older folded cover sequence overprinted by Himalayan fold-thrust movement, Pre to Syntectonic Granitoid, Basic Volcanics, Crystalline complex overprinted by Himalayan fold-thrust movement, Older Cover Sequence folded during Himalayan Fold Thrust movement. [41] (Table.6.5 (k)) (Fig.4.7)

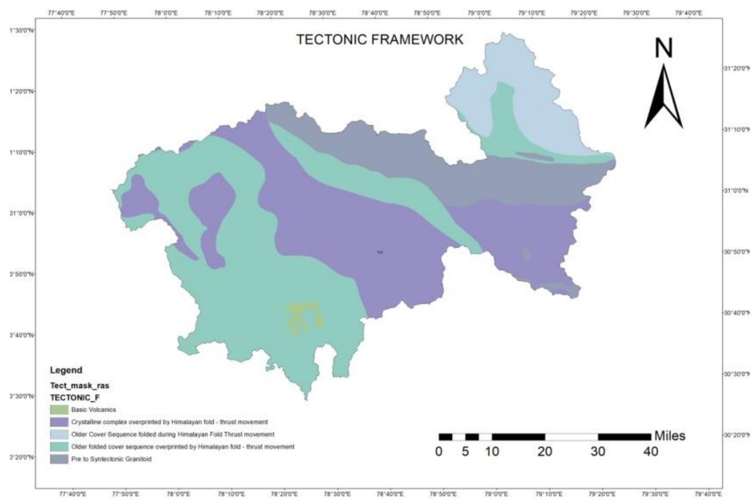


Fig.4.7.Tectonic framework map

4.3.8 EARTHQUAKE MAGNITUDE DISTRIBUTION

For better analysis of earthquake-induced landslides, it was important to take into consideration the magnitude of landslide occurrence. As is evident, with the increase in earthquake magnitude the number of landslides increases. Over 65 Earthquake epicenters (ranging from a magnitude of 3.5 to 6.8) have been considered. With the help of the spline function in ArcGIS, the magnitude distribution was analyzed and categorized into 5 classes. Most of the landslides were seen occurring in a magnitude range of 4-8. (Table.6.5 (g)) (Fig.4.8)

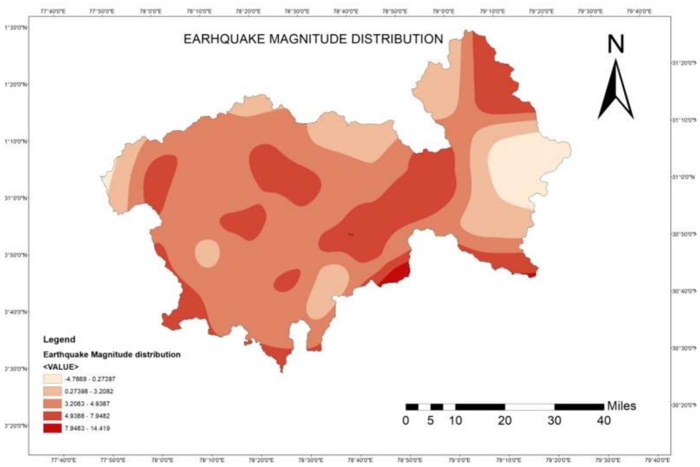


Fig.4.8. Earthquake magnitude distribution map

4.3.9 DISTANCE TO RIVER

The degree of saturation is a crucial factor that influences the slope's stability. The slope's separation from the river aids in forecasting saturation and, consequently, stability. Five classes made up the distance. (Table.6.5(h)) Rivers generally play a big part in landslip vulnerability because they erode the slope's base and cause undercutting processes. The Euclidean Distance is used to compute the distance to rivers. The distance on the river chart is divided into 5 categories, with values ranging from 0 to 30,000 metres.(Fig.4.9)

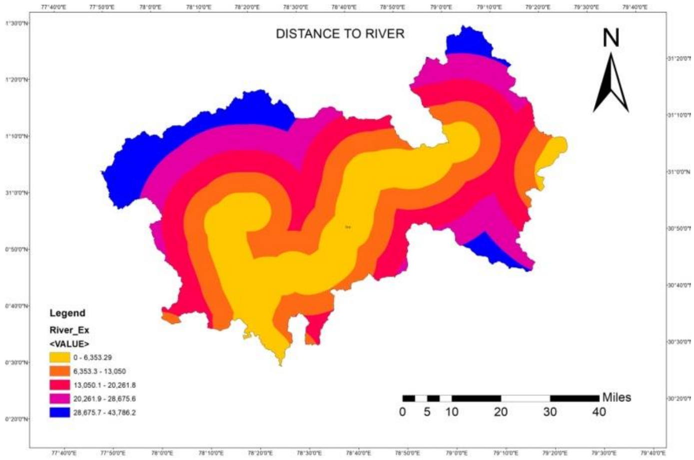


Fig.4.9.Distance to River map

4.3.10 DISTANCE TO ROAD

Since the roads are constructed on the sides of slopes, the occurrence of landslides does affect the construction pattern. It is necessary to analyze this distance for less damage. Table 6.5(i)'s breakdown of the percentage of landslides in each buffer zone reveals that 98% of them are concentrated within 500 m zones. (Fig.4.10)

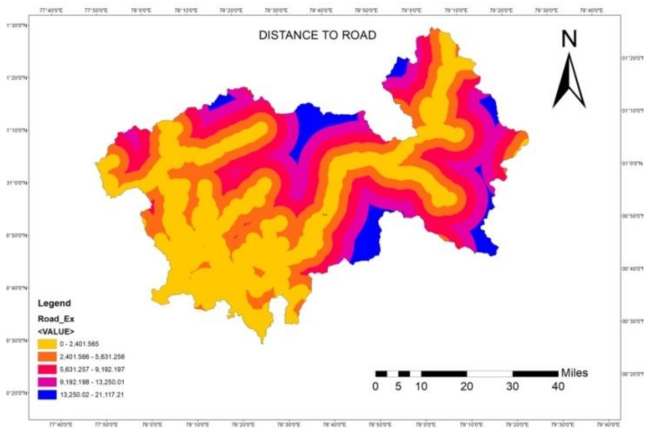


Fig.4.10.Distance to Road map

4.3.11 DISTANCE TO FAULTS

To account for the seismic capacity of the study area it is necessary to take into consideration the distance from faults. For the analysis of earthquake-induced landslides distance from faults plays a major role. [45] Lineaments' distance is divided into 5 categories. Table 6.5(j)’s breakdown of the landslide percentage for each zone reveals that the 1000 m zone contains 33 percent of all landslides. With the increase in faults, the area becomes more susceptible to landslides and earthquakes. The distance to the lineaments is calculated using the GIS tool for Euclidean distance after the lineament data is gathered.(Fig.4.11)

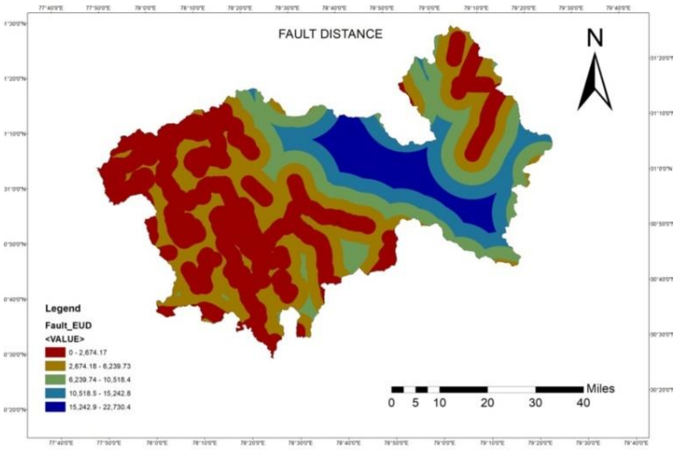


Fig.4.11.Distance to fault map

4.3.12 LANDSLIDE INVENTORY

Over 600 landslide points were considered in and around Uttarkashi for the analysis. Most of these points were concentrated in the west region (Fig.4.12 and Fig.4.13). 80% of the total landslides were chosen to train models, while the rest 20% were used to test them.

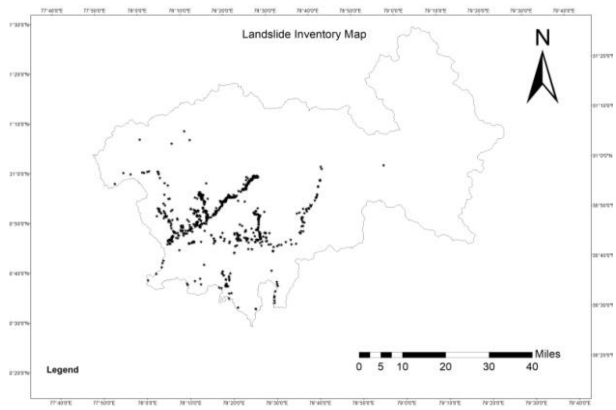


Fig.4.12.Landslide inventory map

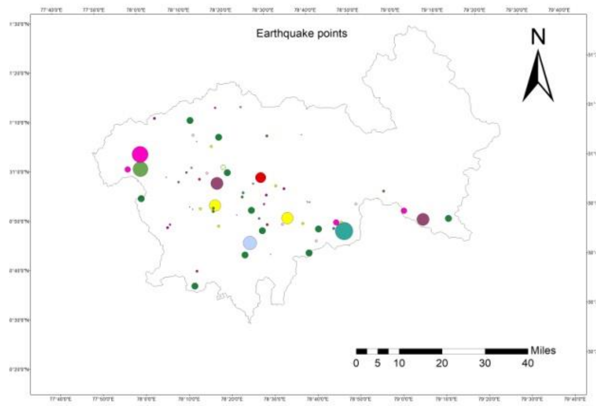
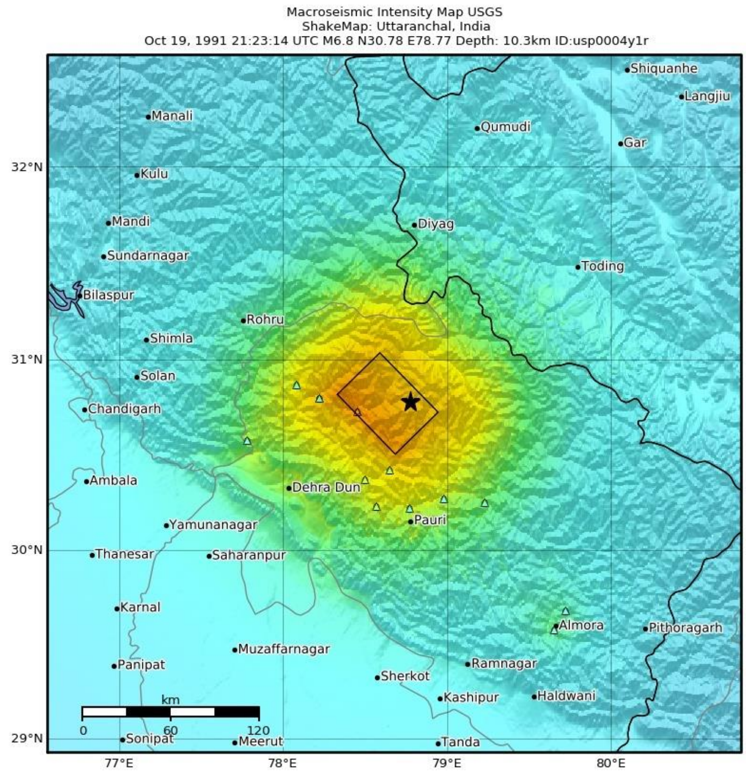


Fig.4.13.Major earthquake points map

CHAPTER 5 - EARTHQUAKE ANALYSIS

5.1 SHAKE MAPS AND ITS ANALYSIS

For earthquake analysis of the study area shake maps for different earthquakes can be used. These maps are obtained from U.S. Geological survey. Peak ground acceleration (PGA) and Peak ground velocity maps can also be obtained respectively and used for dynamic response analysis. Over 65 Earthquake epicenters (ranging from a magnitude of 3.5 to 6.8) in and around Uttarkashi have been considered. The PGA and PGV values obtained from these maps can be considered as causative factors for landslide.



SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
DAMAGE	None	None	None	Very light	Light	Moderate	Moderate/heavy	Heavy	Very heavy
PGA(%g)	<0.0464	0.297	2.76	6.2	11.5	21.5	40.1	74.7	>139
PGV(cm/s)	<0.0215	0.135	1.41	4.65	9.64	20	41.4	85.8	>178
INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Scale based on Worden et al. (2012) Version 1: Processed 2020-06-03T15:23:50Z

△ Seismic Instrument ○ Reported Intensity ★ Epicenter ▭ Rupture

Fig.5.1. M 6.8 - 32 km E of Uttarkashi, India

1991-10-19 21:23:14 (UTC)

30.780°N

78.774°E

10.3 km depth

5.2 PGA AND PGV VALUES ANALYSIS

Factors related to earthquake are also depictive of the earthquake intensity. These mainly consider the peak ground acceleration (PGA), peak ground velocity (PGV), and Arias intensity (AI) values. These values can be obtained from earthquake strong-motion record and the U.S. geological survey map of various locations for different intensity earthquakes.

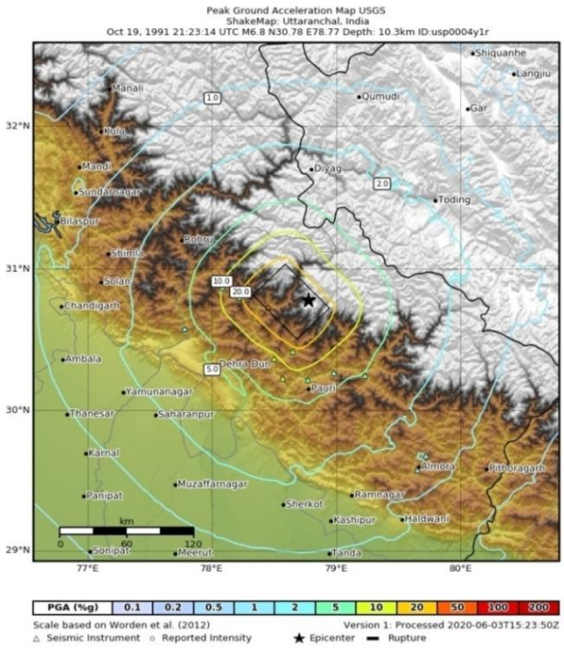


Fig.5.2.Peak ground acceleration (PGA) map for Uttarkashi

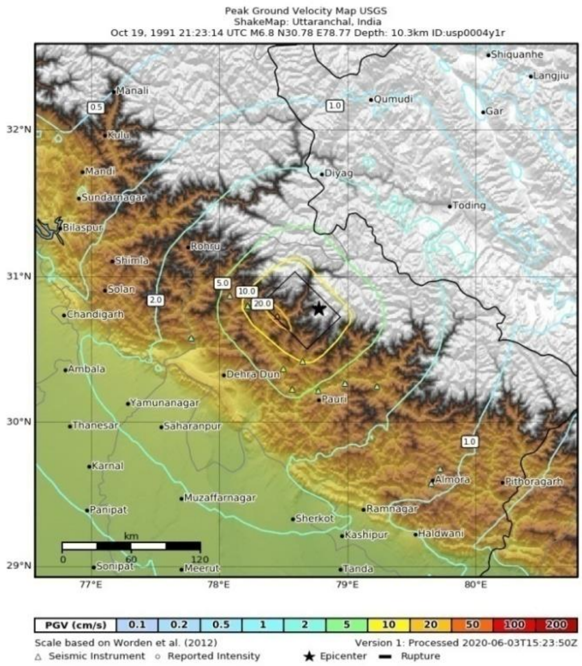


Fig.5.3.Peak ground velocity (PGV) map for Uttarkashi

CHAPTER 6 - METHODOLOGY

Two methods i.e. AHP (Analytical hierarchical process) and Relative frequency have been used for the analysis of earthquake-induced landslides. The major steps involved the selection of area, collection of data, preparation of landslide inventory maps using various landslide triggering factors, and then the final analysis using the above-mentioned methods. These are further explained below. (Fig.6.1)

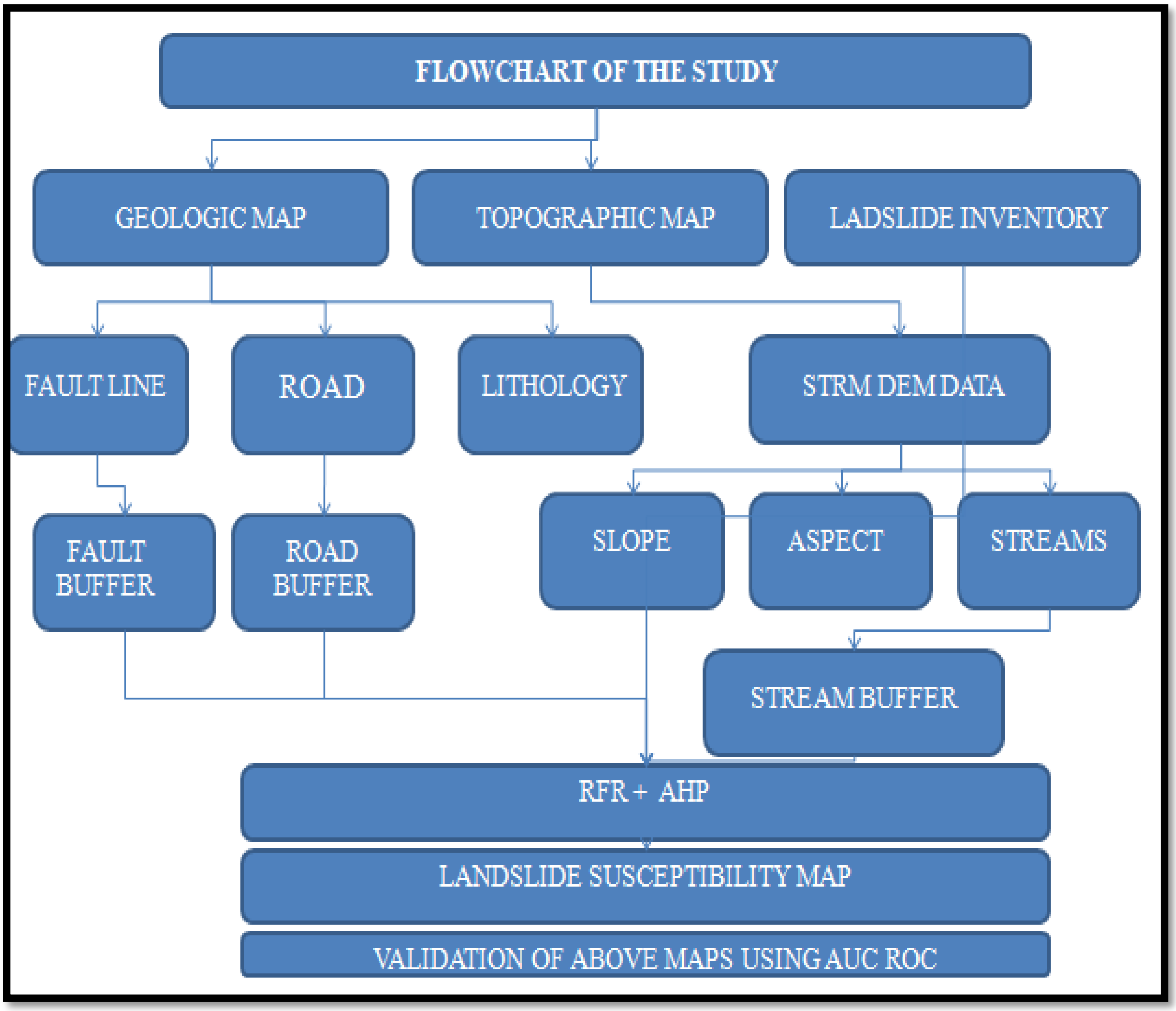


Fig.6.1.Flowchart of the study

6.1 ANALYTICAL HEIRARCHIAL (AHP) PROCESS

AHP stands for analytical hierarchical process which is a multi-criteria decision-making analysis technique (MCDMA) that involves comparison of the various triggering factors associated with earthquake-induced landslides in a pair-wise manner. It includes a preference matrix (Table 6.3) in which a numerical value is assigned to each of the factors based on its relevance compared to others two at a time. The factors are assigned using the SAATY table shown below (Saaty, T. L. 1977, A scaling method for priorities in hierarchical structures. Journal of Mathematical Psychology 15:59–62). (Table 6.2) The matrix is further evaluated to determine the weightage of each along with the consistency index. Later the weights can be combined with the thematic map layers. The Consistency Index (CI) is determined using the following equation:

$$CI = \frac{\lambda - n}{n - 1} \qquad [6.1]$$

Where CI is the consistency index, λ is the Eigen value, and n is the total number of factors that are being considered. The consistency of preference matrix is validated using Consistency Ratio (CR) which is determined using the following equation:

$$CR = \frac{CI}{RI} \qquad [6.2]$$

$$\text{Eigen vector } (V_p) = \sqrt[n]{\text{Product of all Preference values}} \qquad [6.3]$$

$$\text{Weighing coefficient } (C_p) = \frac{\text{Eigen vector of each factor}}{\text{Sum of eigen vectors}} \qquad [6.4]$$

$$D = A * C_p \qquad [6.5]$$

$$\text{Eigen value (E)} = D/C_p \qquad [6.6]$$

$$\lambda_{max} = \frac{\text{Sum of eigen values(E)}}{n} \qquad [6.7]$$

Where CR is the Consistency Ratio and RI is the Random consistency Index of the pair wise preference matrix. The Random consistency index is shown in the table below. (Table 6.1) The consistency index rule is that a Consistency Ratio (CR) less than or equal to 0.1 determines an acceptable preference matrix, while a ratio over than 0.1 indicates that the matrix should be amended.

Table.6.1. Random index (R.I.) up to 15th order of matrix

Order of matrix	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Value of RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48	1.56	1.57	1.59

Table.6.2.Scale for pair-wise comparison

Intensity factor	**Description**	**Explanation**
1	Equal contribution	Two factors contribute equally to the phenomenon
3	Moderate contribution	As per judgment and experience slightly favor one factor over another
5	Essential or strong contribution	Experience and judgment strongly favor one factor over another
7	Very strong contribution	A factor is favored very strongly over another, its effect is visibly harmful
9	Extreme contribution	The evidence favoring one activity over another is of the highest possible order of affirmation
2,4,6,8	Intermediate values	When compromise is needed
Reciprocals	Opposites	Used for inverse comparison

Table.6.3.Preference matrix for AHP

	Elevation	Slope	Aspect	Curvature	Lithology	LULC	Tectonic Framework	Earthquake magnitude	Distance from River	Distance from Road	Fault distribution
Elevation	1	7	9	4	4	3	2	2	2	1/9	1/6
Slope	1/7	1	2	1/4	1/3	¼	1/6	1/5	1/7	1/8	1/6
Aspect	1/9	1/2	1	1/4	1/4	1/5	1/7	1/7	1/8	1/9	1/6
Curvature	1/4	4	4	1	1/2	1/3	1/5	1/3	1/4	1/6	1/3
Lithology	1/4	3	4	2	1	½	1/6	1/4	1/4	1/5	1/3
LULC	1/3	4	5	3	2	1	1/3	1/3	1/3	1/3	1/2
Tectonic Framework	1/2	6	7	5	6	3	1	1/2	2	1/2	3
Earthquake magnitude	1/2	5	7	3	4	3	2	1	2	1/2	3
Distance from River	1/2	7	8	4	4	3	1/2	1/2	1	1/2	2
Distance from Road	9	8	9	6	5	3	2	2	2	1	2
Fault distribution	6	6	6	3	3	2	1/3	1/3	1/2	1/2	1

Table.6.4.Calculation for determination of CR and factor weights for AHP

	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]	[11]	Sum	weights
DEM	0.054	0.136	0.145	0.127	0.133	0.156	0.226	0.263	0.189	0.027	0.013	1.469	0.13
SLOPE	0.008	0.019	0.032	0.008	0.011	0.013	0.019	0.026	0.013	0.031	0.013	0.194	0.02
ASPECT	0.006	0.010	0.016	0.008	0.008	0.010	0.016	0.019	0.012	0.027	0.013	0.146	0.01
CURVATURE	0.013	0.078	0.065	0.032	0.017	0.017	0.023	0.044	0.024	0.041	0.026	0.379	0.03
LITHOLOGY	0.013	0.058	0.065	0.063	0.033	0.026	0.019	0.033	0.024	0.049	0.026	0.410	0.04
LULC	0.018	0.078	0.081	0.095	0.066	0.052	0.038	0.044	0.031	0.082	0.039	0.625	0.06
TECTONIC	0.027	0.117	0.113	0.159	0.199	0.156	0.113	0.066	0.189	0.124	0.237	1.498	0.14
SPLINE	0.027	0.097	0.113	0.095	0.133	0.156	0.226	0.132	0.189	0.124	0.237	1.528	0.14
RIVER EUD	0.027	0.136	0.129	0.127	0.133	0.156	0.057	0.066	0.094	0.124	0.158	1.206	0.11
ROAD EUD	0.484	0.155	0.145	0.190	0.166	0.156	0.226	0.263	0.189	0.247	0.158	2.380	0.22
FAULT EUD	0.323	0.117	0.097	0.095	0.100	0.104	0.038	0.044	0.047	0.124	0.079	1.166	0.11

6.2 RELATIVE FEQUENCY RATIO (RFR) METHOD

Frequency ratio represents a very uncomplicated and efficient framework to analyze landslide induced by earthquake. It is based on the relationship between landslide variables and their distribution. Here, the RFR approach has been used to estimate the risk of earthquake-induced landslides in the area under consideration. Eleven different variables are employed as input landslide factors: slope, aspect, curvature, elevation and proximity to river, road, fault, tectonic framework, lithology, land use, land cover and seismicity of the area. For each class in each causal component, FR and RF are determined using this procedure. Every factor's thematic map is classed using the RF values following the calculation of RF. The association between the occurrence of landslides and the conditioning factor is stronger the higher the FR ratio. Next, the Prediction Rate for each causal factor is determined. Landslip Susceptibility Mapping is created by multiplying the Prediction rate by the classed maps (based on RF) using the Raster Calculator. The mathematical expression for the above method is mentioned as:

$$FR = \frac{\text{total number of pixels with the landslide for each conditioning factor}}{\text{the total number of pixels of landslides}} \qquad [6.8]$$

$$RF = \frac{\text{FR}}{\sum \text{FR (for that conditioning factor)}} \qquad [6.9]$$

$$PR = \frac{\text{RFmax} - \text{RF min}}{(\text{RFmax} - \text{RF min})\text{min}} \qquad [6.10]$$

where PR stands for prediction rate. After doing the above calculations in the excel sheet, LSM can be obtained in ArcGIS with the help of Raster Calculator.

Table.6.5.Frequency ratio results for all the triggering factors

a) Slope

FACTOR	CLASSES	CLASS PIXELS	%CLASS PIXEL	LANDSLIDE PIXELS	%LANDSLIDE PIXEL	FR	RF	RF%	RF(INT)	MAX RF-MIN RF	(MAX-MIN)MIN RF	PR
SLOPE	<15	1248031	14.03	45000	0.09	0.04	0.14	14.27	14	0.129	0.100	1.29
	15-30	2278351	25.60	126900	0.26	0.06	0.22	22.05	22			
	30-45	2623366	29.48	180000	0.37	0.07	0.27	27.16	27			
	45-60	1959505	22.02	93600	0.19	0.05	0.19	18.91	18			
	>60	789018	8.87	35100	0.07	0.04	0.18	17.61	17			

b) Aspect

FACTOR	CLASSES	CLASS PIXELS	%CLASS PIXEL	LANDSLIDE PIXELS	%LANDSLIDE PIXEL	FR	RF	RF%	RF(INT)	MAX RF-MIN RF	(MAX-MIN)MIN RF	PR
ASPECT	FLAT	922992	0.10	27900	0.06	0.03	0.06	6.28	6			
	NORTH	891889	0.10	42300	0.09	0.05	0.10	9.85	9			
	NORTH EAST	894094	0.10	39600	0.08	0.04	0.09	9.20	9			
	EAST	941057	0.11	60300	0.13	0.06	0.13	13.30	13			
	SOUTH EAST	978179	0.11	49500	0.10	0.05	0.11	10.51	10			
	SOUTH	1091297	0.12	75600	0.16	0.07	0.14	14.38	14			
	SOUTH WEST	1044244	0.12	81900	0.17	0.08	0.16	16.28	16			
	WEST	1048438	0.12	60300	0.13	0.06	0.12	11.94	11			
	NORTH WEST	1086081	0.12	43200	0.09	0.04	0.08	8.26	8	**0.100**	**0.100**	**1.00**

c) Curvature

FACTOR	CLASSES	CLASS PIXELS	%CLASS PIXEL	LANDSLIDE PIXELS	%LANDSLIDE PIXEL	FR	RF	RF%	RF(INT)	MAX RF-MIN RF	(MAX-MIN)MIN RF	PR
CURVATURE	<-10	72119	0.01	6300.00	0.01	0.09	0.26	25.55	25.00			
	-10 to -5	631486	0.07	46800.00	0.10	0.07	0.22	21.67	21.00			
	-5 to -3	1229233	0.14	85500.00	0.18	0.07	0.20	20.34	20.00			
	-3 to 1	5757073	0.65	290700.00	0.60	0.05	0.15	14.77	14.00			
	1 to 5	1117722	0.13	49500.00	0.10	0.04	0.13	12.95	12.00			
	>5	111597	0.01	1800.00	0.00	0.02	0.05	4.72	4.00	**0.21**	**0.10**	**2.08**

d) Elevation

FACTOR	CLASSES	CLASS PIXELS	%CLASS PIXEL	LANDSLIDE PIXELS	%LANDSLIDE PIXEL	FR	RF	RF%	RF(INT)	MAX RF-MIN RF	(MAX-MIN)MIN RF	PR
ELEVATION	<1500	609280	6.83	219600.00	45.69	0.36	0.80	80.32	80.00			
	1500-3000	2954941	33.13	261000.00	54.31	0.09	0.20	19.68	19.00			
	3000-4500	2204651	24.72	0.00	0.00	0.00	0.00	0.00	0.00			
	4500-6000	2991892	33.54	0.00	0.00	0.00	0.00	0.00	0.00			
	>6000	158466	1.78	0.00	0.00	0.00	0.00	0.00	0.00	**0.80**	**0.10**	**8.03**

FACTORS	CLASSES	CLASS PIXELS	%CLASS PIXEL	LANDSLIDE PIXELS	%LANDSLIDE PIXEL	FR	RF	RF%	RF(INT)	MAX RF-MIN RF	(MAX-MIN)MIN RF	PR
LITHOLOGY	stromatolitic limestone and slate	2099	0.00	0.00	1.00	0.00	0.00	0.00	0.00			
	garnetiferous schist, gneiss, quartzite	2239	0.00	0.00	2.00	0.00	0.00	0.00	0.00			
	garnetiferous schist, quartzite, amphibolite	323	0.00	0.00	3.00	0.00	0.00	0.00	0.00			
	streaky and banded gneiss.	124709	0.01	0.00	5.00	0.00	0.00	0.00	0.00			
	medium to coarse biotite granite	788323	0.09	0.00	10.00	0.00	0.00	0.00	0.00			
	phyllite, slate,siltstone,qtzite locally gritty	24282	0.00	0.00	11.00	0.00	0.00	0.00	0.00			
	schist, gneiss, migmatite, qrtzite, marble	150579	0.02	0.00	14.00	0.00	0.00	0.00	0.00			
	psammatic gneiss, garneti mica schist, amphibolite	52675	0.01	0.00	18.00	0.00	0.00	0.00	0.00			
	granite	418	0.00	0.00	19.00	0.00	0.00	0.00	0.00			
	schist and quartzite	25738	0.00	0.00	20.00	0.00	0.00	0.00	0.00			
	carbonaceous slate,phyllite,schist, lst,qtzite	1282	0.00	0.00	21.00	0.00	0.00	0.00	0.00			
	white-grey quartzite,schist,carbonaceous dolomite	1800	0.00	0.00	22.00	0.00	0.00	0.00	0.00			
	shale,phyllite,schist,qtzite,dolomite,amphibolite	503	0.00	0.00	23.00	0.00	0.00	0.00	0.00			
	white-grey qtzite,carbonaceous schist,amphibolite	8259	0.00	0.00	24.00	0.00	0.00	0.00	0.00			
	phyllite,schist,amphibolite,lst,qtzite	9222	0.00	0.00	25.00	0.00	0.00	0.00	0.00			
	quartzite and quartz mica schist	122549	0.01	0.00	26.00	0.00	0.00	0.00	0.00			
	gneiss, kyanite schist, quartzite, calc silicate	62858	0.01	0.00	27.00	0.00	0.00	0.00	0.00			
	basic rock (amphibolite)	3916	0.00	5400.00	28.00	1.38	0.21	21.32	21.00			
	gneiss, mica schist with marble band	105100	0.01	18000.00	29.00	0.17	0.03	2.65	2.00			
	unmapped	1238902	0.14	0.00	30.00	0.00	0.00	0.00	0.00			
	garnetiferous gneiss with bands of marble	153385	0.02	900.00	31.00	0.01	0.00	0.09	0.00	**0.21**	**0.10**	**2.13**

	slate, carb. shale, quartzite, siltstone, phyllite	278913	0.03	0.00	32.00	0.00	0.00	0.00	0.00			
	shale, slate, siltstone, quartzite	153	0.00	0.00	33.00	0.00	0.00	0.00	0.00			
	quartzite with mica schist partings	49733	0.01	6300.00	34.00	0.13	0.02	1.96	1.00			
	marble band	19068	0.00	4500.00	35.00	0.24	0.04	3.65	3.00			
	marble with quartzite partings	23257	0.00	1800.00	36.00	0.08	0.01	1.20	1.00			
	quartz-mica-chlorite-hornblend schist & gneiss	349762	0.04	9000.00	37.00	0.03	0.00	0.40	0.00			
	phyllite, qtz, shale,dolomite, tuff with dolerite	559438	0.06	92700.00	38.00	0.17	0.03	2.56	2.00			
	epidiorite	10612	0.00	4500.00	39.00	0.42	0.07	6.55	6.00			
	shale,quartzite, limestone and conglomerate	40086	0.00	7200.00	40.00	0.18	0.03	2.78	2.00			
	slate, quartzite, dolomite with cherty limestone	46113	0.01	900	41.00	0.02	0.00	0.30	0.00			
	grey sand, silt and clay	13904	0.00	12600	42.00	0.91	0.14	14.01	14.00			
	quartzite,slate,phyllite,dolomite with basics	671030	0.08	66600	43.00	0.10	0.02	1.53	1.00			
	quartzite, phyllite/slate and limestone	4502	0.00	0	44.00	0.00	0.00	0.00	0.00			
	schist, gneiss, quartzite and amphibolite	583	0.00	0	45.00	0.00	0.00	0.00	0.00			
	streaky gneiss, quartzite	54365	0.01	900	46.00	0.02	0.00	0.26	0.00			
	amphibolite	2861	0.00	0	47.00	0.00	0.00	0.00	0.00			
	basic rock	1531	0.00	0	48.00	0.00	0.00	0.00	0.00			
	gravel, pebble, sand, silt and clay	51498	0.01	21600	49.00	0.42	0.06	6.48	6.00			
	basic rock (epidiorite)	9896	0.00	4500	50.00	0.45	0.07	7.03	7.00			
	quartzite and slate with basic metavolcanics	772818	0.09	90000	51.00	0.12	0.02	1.80	1.00			
	basic meta-volcanics	96419	0.01	26100	52.00	0.27	0.04	4.18	4.00			
	basic rocks (epidiorite)	75211	0.01	6300	53.00	0.08	0.01	1.29	1.00			
	quartzite, slate, lensoidal limestone	60366	0.01	16200	54.00	0.27	0.04	4.15	4.00			

	and tuff											
	limestone, dolomite, shale and cherty quartzite	22711	0.00	7200	55.00	0.32	0.05	4.90	4.00			
	gneiss and quartz mica schist	253885	0.03	40500	56.00	0.16	0.02	2.47	2.00			
	gneiss, schist and amphibolite	203703	0.02	7200	57.00	0.04	0.01	0.55	0.00			
	garnet biotite gneiss and schist	130797	0.01	8100	58.00	0.06	0.01	0.96	0.00			
	quartzite, schist, slate with basic volcanics	42298	0.00	9900	59.00	0.23	0.04	3.62	3.00			
	slate quartzite, dolomite with cherty limestone	21825	0.00	3600	60.00	0.16	0.03	2.55	2.00			
	medium to coarse grained biotite granite	356519	0.04	0	61.00	0.00	0.00	0.00	0.00			
	purple, green qtzite,shale, siltstone,diamictite	476543	0.05	0	62.00	0.00	0.00	0.00	0.00			
	limestone, siltstone, marl and shale	187974	0.02	0	65.00	0.00	0.00	0.00	0.00			
	variegated shale, dolomite and siliceous limestone	57667	0.01	0	66.00	0.00	0.00	0.00	0.00			
	shale, sandstone with conglomerate	62536	0.01	0	67.00	0.00	0.00	0.00	0.00			
	orthoquartzite with shale bands	126595	0.01	0	68.00	0.00	0.00	0.00	0.00			
	shale with shaly limestone	40958	0.00	0	69.00	0.00	0.00	0.00	0.00			
	ferruginous limestone	21436	0.00	0	70.00	0.00	0.00	0.00	0.00			
	carb. shale, siltstone, sandstone with nodules	5699	0.00	0	71.00	0.00	0.00	0.00	0.00			
	kyanite schist and gneiss	84825	0.01	900	72.00	0.01	0.00	0.16	0.00			
	schist, quartzite, limestone, carbonaceous slate	193535	0.02	0	73.00	0.00	0.00	0.00	0.00			
	slate,carbo. shale, quartzite, siltstone phyllite	98109	0.01	0	74.00	0.00	0.00	0.00	0.00			
	biotite, hornblende granite	246717	0.03	0	75.00	0.00	0.00	0.00	0.00			
	basal conglomerate and massive quartzite	19649	0.00	0	76.00	0.00	0.00	0.00	0.00			
	slate,quartzite,phyllite,siltstone and gritstone	404	0.00	0	77.00	0.00	0.00	0.00	0.00			

	shale, slate, siltstone & interbeds of quartzite	153	0.00	0	78.00	0.00	0.00	0.00	0.00			
	high grade schist, gneiss, calc silicate, marble	3281	0.00	0	79.00	0.00	0.00	0.00	0.00			
	quartzite, schist/phyllite and amphibolite	182328	0.02	720 0	82.00	0.04	0.01	0.61	0.00			
	splintery shale with nodular limestone	44	0.00	0	93.00	0.00	0.00	0.00	0.00			
	shale, quartzite, limestone and dolomite	3776	0.00	0	100.00	0.00	0.00	0.00	0.00			
	quartzite, schist	1168	0.00	0	105.00	0.00	0.00	0.00	0.00			

e) Lithology

f) LULC

FACTORS	CLASSES	CLASS PIXELS	%CLASS PIXEL	LANDSLID E PIXELS	%LANDSL IDE PIXEL	FR	RF	RF%	RF(INT)	MAX RF-MIN RF	(MAX-MIN)MIN RF	PR
LULC	20498	0.23	9000	1.87	0.44	0.32	32.04	32.00	20498			
	2820110	31.62	157500	32.77	0.06	0.04	4.08	4.00	2820110			
	51419	0.58	20700	4.31	0.40	0.29	29.38	29.00	51419			
	45736	0.51	12600	2.62	0.28	0.20	20.10	20.00	45736			
	1435364	16.09	22500	4.68	0.02	0.01	1.14	1.00	1435364			
	1422097	15.94	0	0.00	0.18	0.13	13.26	13.00	1422097			
	3123925	35.02	258300	53.75	0.00	0.00	0.00	0.00	3123925			
	20498	0.23	9000	1.87	0.44	0.32	32.04	32.00	20498.00	**0.32**	**0.10**	**3.20**

g) Earthquake magnitude distribution

FACTORS	CLASSES	CLASS PIXELS	%CLASS PIXEL	LANDSLID E PIXELS	%LANDSL IDE PIXEL	FR	RF	RF%	RF(INT)	MAX RF-MIN RF	(MAX-MIN)MIN RF	PR
Earthquake magnitude distribution	<0	453571	5.09	0.00	0.00	0.00	0.00	0.00	0			
	0-4	3220387	36.11	124200.00	25.84	0.04	0.36	36.00	36			
	4-8	5199208	58.29	356400.00	74.16	0.07	0.64	64.00	63			
	8-12	37398	0.42	0.00	0.00	0.00	0.00	0.00	0			
	>12	8657	0.10	0.00	0.00	0.00	0.00	0.00	0	**0.64**	**0.10**	**6.39**

h) Distance to River

FACTORS	CLASSES	CLASS PIXELS	%CLASS PIXEL	LANDSLIDE PIXELS	%LANDSLIDE PIXEL	FR	RF	RF%	RF(INT)	MAX RF-MIN RF	(MAX-MIN)MIN RF	PR
Distance to River	<5000	1763346	19.77	259200	53.93	0.15	0.59	59.22	59			
	5000-10000	1722254	19.31	100800	20.97	0.06	0.24	23.58	23			
	1000-20000	3098055	34.73	112500	23.41	0.04	0.15	14.63	14			
	20000-30000	1575705	17.67	6300	1.31	0.00	0.02	1.61	1			
	>30000	759861	8.52	1800	0.37	0.00	0.01	0.95	0	**0.58**	**0.10**	**5.82**

i) Distance to road

FACTORS	CLASSES	CLASS PIXELS	%CLASS PIXEL	LANDSLIDE PIXELS	%LANDSLIDE PIXEL	FR	RF	RF%	RF(INT)	MAX RF-MIN RF	(MAX-MIN)MIN RF	PR
Distance to Road	<0	3306079	37.07	471600.00	98.13	0.14	0.97	97.16	97			
	0-1000	2233305	25.04	8100.00	1.69	0.00	0.02	2.47	2			
	1000-2000	1660484	18.62	900.00	0.19	0.00	0.00	0.37	0			
	2000-3000	1189798	13.34	0.00	0.00	0.00	0.00	0.00	0			
	3000-4000	529555	5.94	0.00	0.00	0.00	0.00	0.00	0	**0.97**	**0.10**	**9.71**

j) Distance to fault

FACTORS	CLASSES	CLASS PIXELS	%CLASS PIXEL	LANDSLIDE PIXELS	%LANDSLIDE PIXEL	FR	RF	RF%	RF(INT)	MAX RF-MIN RF	(MAX-MIN)MIN RF	PR
Distance to Fault	<1000	1462740	16.40	160200	33.33	0.11	0.54	54.40	54			
	1000-5000	3664375	41.08	306000	63.67	0.08	0.41	41.48	41			
	5000-10000	1793079	20.10	13500	2.81	0.01	0.04	3.74	3			
	10000-15000	1200108	13.46	900	0.19	0.00	0.00	0.37	0			
	>15000	798919	8.96	0	0.00	0.00	0.00	0.00	0	**0.54**	**0.10**	**5.44**

k) Tectonic framework

FACTORS	CLASSES	CLASS PIXELS	%CLASS PIXEL	LANDSLIDE PIXELS	%LANDSLIDE PIXEL	FR	RF	RF%	RF(INT)	MAX RF-MIN RF	(MAX-MIN)MIN RF	PR
Tectonic framework	Older folded cover sequence overprinted by Himalayan fold - thrust movement	3619733	40.58	359100	74.72	0.10	0.60	59.50	59	**0.60**	**0.10**	**5.95**
	Pre to Syntectonic Granitoid	1379339	15.46	0	0.00	0.00	0.00	0.00	0			
	Basic Volcanics	64243	0.72	1800	0.37	0.03	0.17	16.81	16			
	Crystalline complex overprinted by Himalayan fold - thrust movement	3030444	33.98	119700	24.91	0.04	0.24	23.69	23			
	Older Cover Sequence folded during Himalayan Fold Thrust movement	825462	9.25	0	0.00	0.00	0.00	0.00	0			

CHAPTER 7 - RESULT AND DISCUSSION

7.1 EIL SUSCEPTIBILITY MAP BY AHP MODEL

In this investigation, the consistency ratio's ultimate value was discovered to be less than 0.10. (i.e.0.0748). (Table 7.2) It indicates that the weights were suitable and the preference matrix comparisons were consistent. The distance to a road map was given the most weight. Furthermore determined to be useful were the tectonic framework, elevation parameters, and earthquake magnitude. Also identified the other layers—slope, aspect, curvature, distance to river and fault, lithology, and LULC—as being less significant.

Table.7.1.Calculation of weighing coefficients for various factors

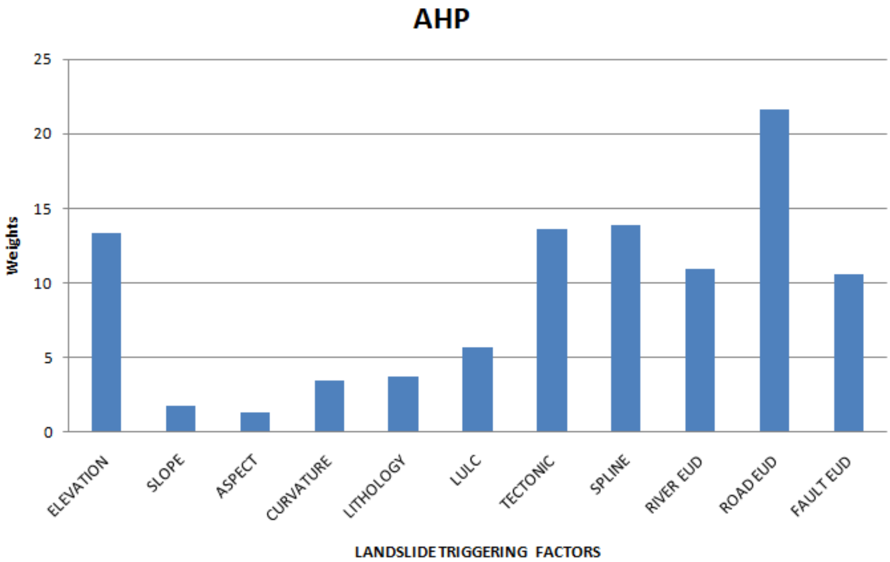
FACTORS	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]	[11]	Eigen vector (Vp)	Weighing coefficient (Cp)	D= A*Cp	EIGEN VALUE (E)=D /Cp
Elevation	1.00	7.00	9.00	4.00	4.00	3.00	2.00	2.00	2.00	0.11	0.17	1.74	0.12	1.65	14.28
Slope	0.14	1.00	2.00	0.25	0.33	0.25	0.17	0.20	0.14	0.13	0.17	0.27	0.02	0.21	11.70
Aspect	0.11	0.50	1.00	0.25	0.25	0.20	0.14	0.14	0.13	0.11	0.17	0.21	0.01	0.16	11.67
Curvature	0.25	4.00	4.00	1.00	0.50	0.33	0.20	0.33	0.25	0.17	0.33	0.51	0.03	0.40	11.90
Lithology	0.25	3.00	4.00	2.00	1.00	0.50	0.17	0.25	0.25	0.20	0.33	0.57	0.04	0.44	11.61
Lulc	0.33	4.00	5.00	3.00	2.00	1.00	0.33	0.33	0.33	0.33	0.50	0.88	0.06	0.67	11.53
Tectonic	0.50	6.00	7.00	5.00	6.00	3.00	1.00	0.50	2.00	0.50	3.00	2.06	0.14	1.69	12.34
Magnitude Earthquake	0.50	5.00	7.00	3.00	4.00	3.00	2.00	1.00	2.00	0.50	3.00	2.11	0.14	1.73	12.35
River distance	0.50	7.00	8.00	4.00	4.00	3.00	0.50	0.50	1.00	0.50	2.00	1.70	0.11	1.33	11.78
Road distance	9.00	8.00	9.00	6.00	5.00	3.00	2.00	2.00	2.00	1.00	2.00	3.49	0.23	3.09	13.35
Fault distance	6.00	6.00	6.00	3.00	3.00	2.00	0.33	0.33	0.50	0.50	1.00	1.53	0.10	1.58	15.58

Table.7.2.Final values of λ_{max}, consistency index and consistency ratio

λ_{max}	CI	CR
12.554	0.114	0.0748

The following equation was then used to construct the landslip susceptibility index:

$$LSI_{AHP} = (Slope \times W_{AHP}) + (Aspect \times W_{AHP}) + (Elevation \times W_{AHP}) + (Curvature \times W_{AHP}) + (Distance\ to\ Roads \times W_{AHP}) + (Distance\ to\ River \times W_{AHP}) + (Tectonic\ Framework \times W_{AHP}) + (Earthquake\ Magnitude \times W_{AHP}) + (Distance\ to\ Faults \times W_{AHP}) + (Lithology \times W_{AHP}) + (LULC \times W_{AHP}) \quad [7.1]$$



Graph.7.1.Weights of different triggering factors

Based on natural breaks, the resulting LSI-map was divided into five classes (very low, low, moderate, high, and very high) to establish the class intervals.

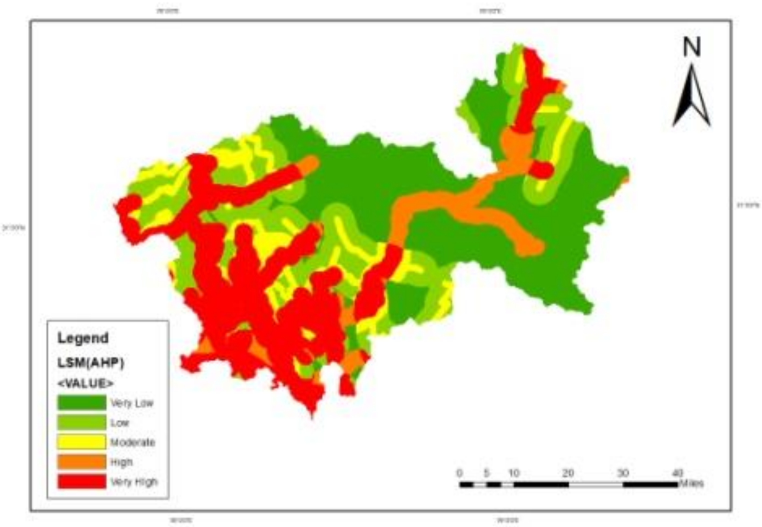


Fig. 7.1.AHP based earthquake induce landslide susceptibility map

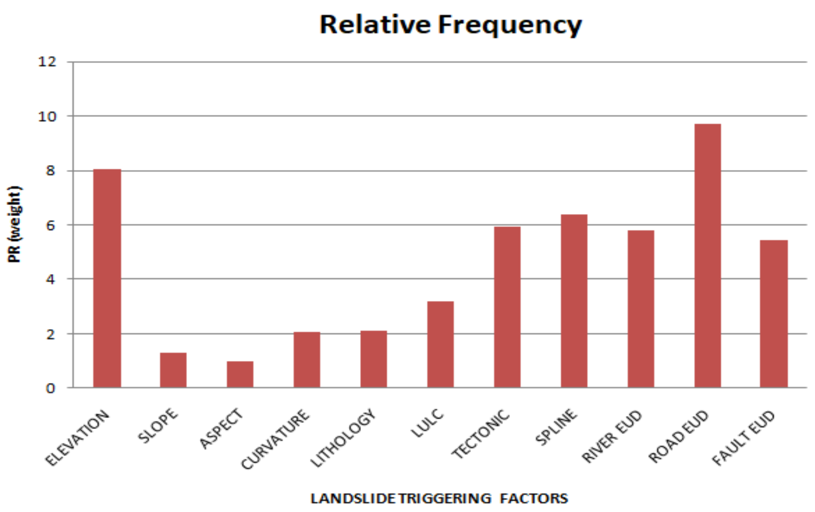
Table.7.3. Landslide based Coincidence table for AHP

S.No.	CLASS	%CLASS PIXEL	%LANDSLIDE PIXEL
1.	Very low	34.12	0
2.	Low	19.97	0.57
3.	Moderate	8.82	1.32
4.	High	8.38	2.99
5.	Very high	28.71	95.13

7.2 **EIL SUSCEPTIBILITY MAPPING BY RFR MODEL**

The weights for each class of each landslide triggering element were used to create the FR technique. The FR ratio was determined by examining the relationship between 11 parameters and the likelihood of landslides. Further calculations are done using the determined prediction rates as follows:

$$LSI= (PR_{elevation}\ x\ Elevation) + (PR_{slope}\ x\ Slope) + (PR_{curvature}\ x\ Curvature) + (PR_{aspec}\ x\ Aspect) + (PR_{distance\ to\ road}\ x\ Distance\ to\ roads) + (PR_{distance\ to\ rivers}\ x\ Distance\ to\ rivers) + (PR_{distance\ to\ fault}\ x\ Distance\ to\ fault) + (PR_{tectonic\ framework}\ x\ Tectonic\ framework) + (PR_{earthquake\ magnitude}\ x\ Earthquake\ magnitude) + (PR_{lithology}\ x\ Lithology) + (PR_{LULC}\ x\ LULC) \quad [7.2]$$



Graph.7.2.Prediction rate of different triggering factors

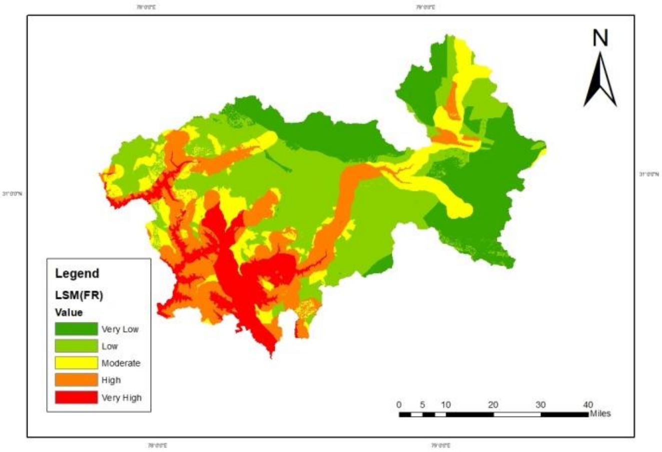


Fig.7.2.Relative Frequency based earthquake induce landslide susceptibility map

Table.7.4.Landslide based Coincidence table for Relative frequency

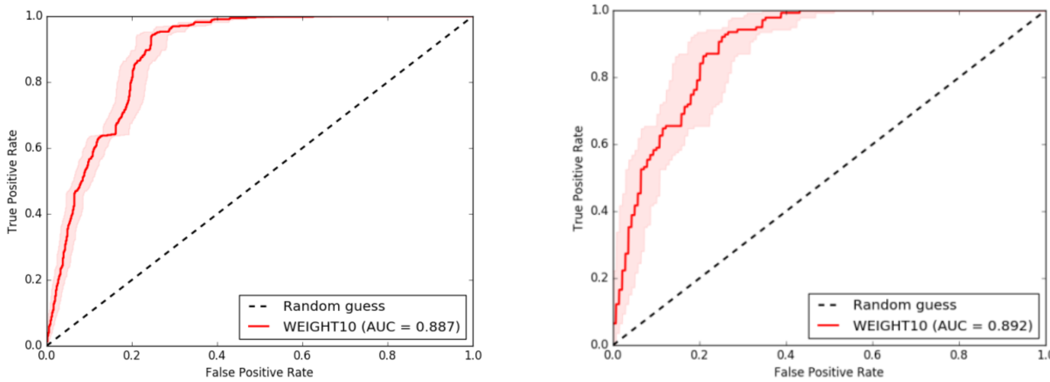
S.No.	CLASS	%CLASS PIXEL	%LANDSLIDE PIXEL
1.	Very low	23.92	0
2.	Low	33.36	0.56
3.	Moderate	14.02	2.24
4.	High	18.18	35.58
5.	Very high	10.52	61.61

7.3 VALIDATION OF ABOVE SUSCEPTIBILITY MAPS

The area under curve (AUC) approach can be used to visually validate the earthquake-induced landslip susceptibility map. (Fig.7.1 and Fig.7.2) The training (80%) and validation (20%) landslide data sets for this investigation were chosen on a random basis. The success rate was calculated by contrasting the landslide susceptibility maps generated by each model with the landslide training data sets. The created landslide susceptibility maps induce by earthquake and the chosen validation landslip datasets were compared to validate the prediction rate.

7.3.1 AHP Validation

The validation results showed that the AHP model obtained 89.2% and 88.7% success and prediction rates respectively. (Fig.7.3)

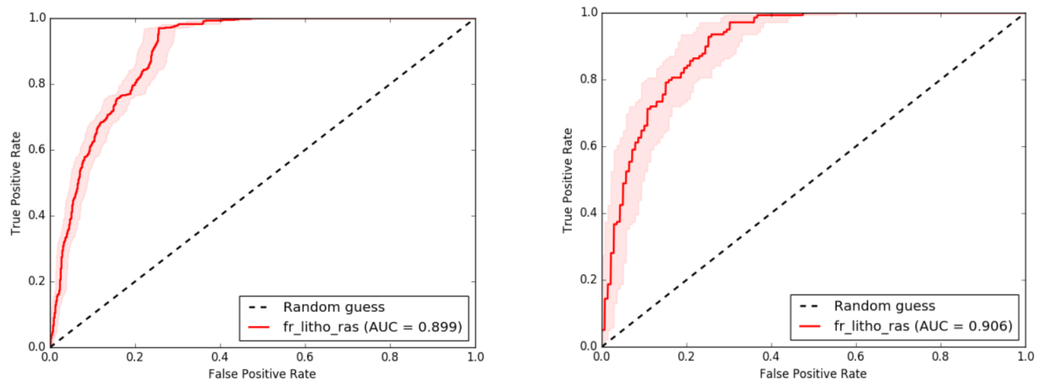


a) b)

Fig.7.3.AHP AUC CURVES

7.3.2 Relative frequency Validation

The validation results showed that the ensemble model obtained 89.9% and 90.6% success and prediction rates respectively. (Fig.7.4)



a) b)

Fig.7.4.RFR AUC CURVES

CHAPTER 8 - CONCLUSION AND FUTURE SCOPE

8.1 CONCLUSION

Results obtained in this study support the following conclusions:

i) For earthquake-induced LSM in the current investigation, a combined FR and AHP approach was used. The model could give success and prediction rates of 89.9% and 90.6%, respectively, according to the validation data (FR gave greater values, hence considered.

ii) Expert judgment along with factor weights from FR was used to calculate the weighting of all eleven AHP factor values. The final values of consistency ratio give satisfactory results (0.0748) and hence the preference matrix can be used for future analysis.

iii) According to the aforementioned findings, a large portion of Uttarkashi is located in a zone of high susceptibility. In comparison to the AHP map, the relative frequency model provides more accurate results.

iv) In order to reduce the risk of landslides and to take appropriate precautions, such a map may be useful for planners and decision-makers for land-use planning, slope management, and earthquake resistance in the research region.

8.2 LIMITATIONS

Following are the major limitations associated with the project

i) There is a significant lack of methods that are more practical in nature for the overall evaluation of risk and zonation of hazard on the basis of current knowledge along with proper strategy for mitigation.

ii) A thorough correlation between the epicenter or the major fault location and that of the landslide (induce by earthquake) must be established and examined.

iii) Clarifying the physical and mechanical properties of unconsolidated volcanic sediments is necessary because they can induce flow-type landslides with lengthy travel distances that can occur far from the epicentre.

iv) In terms of effective disaster mitigation, precise risk assessment and hazard zoning methodologies should be created to encourage sensible land-use and prevent damage from earthquake-induced landslides.

v) In terms of the effectiveness of technological preventive measures, it has already been established that the majority of those now in place, which were initially put in place to stabilize landslides brought on by rainfall, also served earthquake-induced landslides quite effectively.

vi) Most of the research work is largely concerned with the near distant triggering landslides but the far-distant triggering is an important concern that should have been studied and analyzed more among the scientific community.

8.3 LANDSLIDE MITIGATION MEASURES

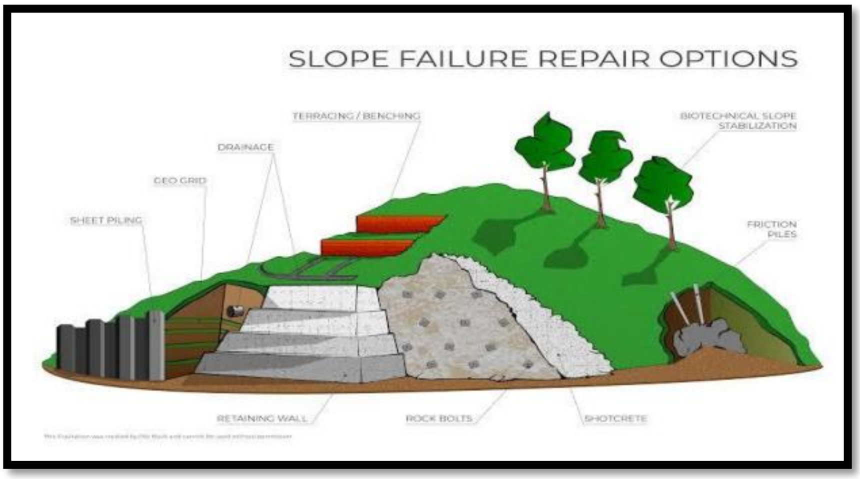


Fig.8.1.Slope Failure Repair Options

Along with landslide pattern analysis, research, fatality study and variation probability certain mitigation measures are necessary to reduce the aftermath of such landslides.(Fig8.1)

Following steps can be taken to ensure the safety against landslides induced with earthquake.

i) <u>Real time of active landslide</u>: The majority of monitoring is done using monitoring prisms and repetitive geodetic surveys, which give accurate information on the magnitudes and rates of horizontal and vertical ground movements.

ii) <u>Gabion walls</u> -wire mesh filled with rocks and boulder: The combination of the Implant deterrence foundation piles along with implant retaining structures can prevent landslide induced by earthquakes of larger magnitude and heavy downpour. The piles inserted into the ground hold soil and allows the ground water to move downward through the gap between piles. The retaining walls ensure support to the surfaces with slopes by resisting movement due to lateral force and pressure.

iii) Rock bolting: Rock bolts work by 'knitting' the rock mass firmly enough to stop it from moving around too much and becoming too loose, which would cause it to fail by unravelling (piece by piece). Rock bolts, unlike conventional anchor bolts, can be "seized" along their whole length by small shearing in the rock mass, hence they are not completely dependent on their pullout strength.

iv) Geogrid: Made of geosynthetic material a geogrid helps in reinforcing the soil and improving strength. This helps in stress distribution to larger area.

v) Biotechnical slope stabilization: as the name suggestion man made structural elements are used in combination with vegetation in an integrated manner which not only has mechanical advantages but also hydrological.

vi) Shotcrete: application of shortcrete can be done using two different methods i.e. dry mix process and the wet mix process. Method type is chosen on the basis of site requirements. Depending upon availability of resources dry mix method is preferred.

vii) Flexible debris-resisting: One method for reducing natural terrain landslides is the use of flexible barriers, which are mostly made of steel ring nets mounted between horizontal steel ropes spanning between steel poles and fixed into the ground. The benefits of flexible barriers include the fact that they are less aesthetically intrusive than reinforced concrete barriers and very simple to construct on naturally steep terrain. Although flexible barriers have been used for more than 20 years as a preventative measure against boulder and rock falls, using them to withstand the force of landslip debris on natural terrain is a relatively new idea.

viii) Other techniques:

- Heat treatment
- Vertical (small diameter) boreholes with pumping or self draining
- Protective rock/concrete blocks against erosion
- Anchors with electosmotic pressure
- Crib-block walls

- Stone or lime/cement columns
- Caissons
- Construction of buttress counter-forts of coarse-grained materials during landslide
- Sheet – with metallic or polymer reinforcement
- Internal slop reinforcement
- Surface drains to divert water from flowing onto the slide area
- Micropiles
- Freezing
- Cast-in situ reinforced concrete walls Reinforced earth retaining structures with strip

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LIST OF CONFERENCES

S.NO	Name of research paper	Name of conference	Organized By	Conference date and Venue	Current status	Proceedings and Publications
1.	Earthquake-Induced Landslide Hazard Assessment of Uttarkashi district, using multiple criteria decision making (MCDM) methods	5th International Conference on Recent Advancements in Engineering and Technology (ICRAET-2023)	Institute for Engineering Research and Publication (IFERP)	19th-20th May'23 Bengaluru, India	Accepted and proceedings started ISBN: 978-93-92105-53-1	Submitted to Web of Science Book Citation Index and to SCOPUS for evaluation and indexing.