

Landslide susceptibility analysis using GIS and Analytical Hierarchy Process (AHP) approach for Disaster risk reduction in the mountainous region: a case study of lesser Himalayan region

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Abstract — Landslide incidents result in significant monetary losses, fatalities, and irrevocable damage to the natural landscape. The landslide inventory mapping method is covered in this study using AHP approach. Here, we have employed seven distinct landslide-affecting characteristics, including slope (S), aspect (A), curvature (C), distance from drainage (DfD), Lineament density (LD), Lithology (L) and Land use Land cover (LULC). The Analytic Hierarchy Process (AHP) method was used to calculate the association between the landslide-impacting elements and historical landslide positions to create the Landslide Susceptible Maps (LSMs). The AHP model assigns a weight to each factor, that will get added and end up giving LSI (Landslide susceptibility index). The region under investigation was divided into four susceptibility classifications, ranging from extremely low to scarring, based on the LSI that was generated. Using current landslide inventory information, the LSMs were checked and verified. The AHP model's total prediction accuracy is 72.9%. Susceptibility maps may be used to determine the most difficult regions, through this essential landslide investigation can be done, which will further help in regional development planning for reducing the risk of disaster.

Keywords— GIS, LSI, LSZ, AHP, DEM

I. Introduction

In downhill geomorphic zones, the physical phenomenon known as landmass movement allows enormous volumes of soil, regolith's, and rubble to roll down the slope in a downward direction. When a material's power is sufficient to surpass the shear strength of the soil, it results in a primarily geological event. The research region's physiographic, geomorphic, geological and hydrological configurations influence the occurrence of landslides. In steep areas, landslides are a dangerous and erratic event that can cause slope collapse results in both financial losses and deaths [1]. In hilly terrain, shifting massive landmasses can occasionally alter river paths, drainage patterns and topography. Landslides have a significant influence on a variety of phenomena, including floods in some circumstances, interruption of road and building projects, soil loss, both wildlife and human loss and deforestation [2]. In the Indian subcontinent, intense monsoon rains are mostly responsible for landmass displacement and slope

collapse; but, in the Himalayan belt, seismic activity has made landfalls quite common [3]. Due to restricted accessibility, compiling landslide data in hilly areas is a particularly difficult undertaking. Remote sensing data might be useful in this situation because gathering Techniques for gathering data including field inspections can be time- and money-consuming. Qualitative approaches depend on expert judgements and are subjective; they describe danger zones in detail. Two more categories can be used to categorise qualitative techniques: The first category is the geomorphologic study, in which the susceptibility to landslides is assessed directly, either on-site or by examining aerial photographs and satellite pictures. Using specialised information, developing landslide susceptibility by establishing an immediate comparison of recent landslides and the contributing terrain characteristics is possible. In the second category, a qualitative map combination known as a landslide susceptibility map is produced by combining several landslide impact factor maps. AHP is extensively employed in the process of making decisions and is applied to a wide range of geoscience fields, including cultural heritage, space planning, flood danger, and vulnerability of coastal areas [4]. Since the amounts of weight are assigned to subcategories of thematic maps on the basis of the in-depth knowledge of experts in the field, a landslide inventory map is not necessary. The subjectivity of the specialists participating may significantly impact a map produced using qualitative approaches. By identifying slopes and valleys that are more vulnerable to instability processes in mountainous regions, the AHP technique helps to reduce potential dangers related to these occurrences [5].

II. Study Area

Between latitudes 30° 19' 00" and 30° 49' North and longitudes 78° 49' and 79° 21' 13" East is the Rudraprayag district, which spans an area of around 2439 km² and is included in surveys of India Toposheet Nos. 53J and 53N. The district, which has its administrative centre at Rudraprayag Town, is made up of three tehsils, namely Okhimath, Rudraprayag, and Jakholi, as well as three

development blocks, namely Augustmuni, Jakholi, and Okhimath. It is accessible by a motorable, metalled road from Rishikesh and Dehradun. There are no rail connections in the area. The district's 1372 km of roadways connect its major towns to its administrative centre. The sole national roadway connects Rishikesh to Badrinath and follows the Ganga and Alaknanda rivers.

III. Datasets

For landslide susceptibility, we should have knowledge about all the factors that are responsible for the cause of landslides. The major factors responsible for landslide occurrence are slope steepness and morphology, seismicity, climate, vegetation, land use, surface and bedrock lithology and structure, stream evolution, human activities and groundwater conditions. Variation in the thematic data is normal as it depends on the methods used to acquire it, scale and type.

The information about landslides that occurred in Rudraprayag district is acquired from the Bhukosh website. For the analysis of these landslides, we can use Google Earth Pro. In our research, we have downloaded the DEM for generating slope, aspect, curvature and distance from drainage inventory maps. With the help of this archived information and the location of concerned landslides in this district, we have prepared the landslide inventory map. Using this gathered information and inventory map we can make our understanding clearer about the responsible factors that affect a landslide or are the main cause for triggering landslides.

In our research, we have converted the concerned factors into vector data types using GIS software. The downloaded DEM file was used to calculate the slope angle, aspect, curvature and Distance from drainage. The classification of slope is done in 5 parts. In aspect factor 8 directions were considered. For the curvature map if the value is negative then it will be considered concave, for convex the value of curvature should be positive and for flat region curvature value is zero. The lithology map was obtained from a 1:208,555-scale geological map. LULC maps for this study area are downloaded from ESRI.

The DEM was used to compute the distance from the drainage. Five classes of the distance from drainage were determined.

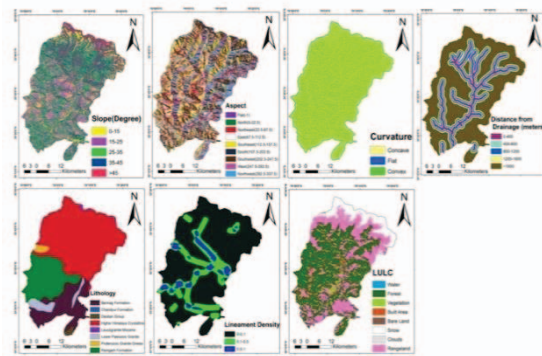


Fig. 1. Thematic layers of current research area.

IV. Methodology

Every landslide evaluation starts with gathering the facts and information that are already known about the region in consideration. Landslide susceptibility mapping depends on environmental elements and landslide inventory, including DEM. In this study, we are considering seven factors that are Lithology (L), Aspect (A), Slope (S), Curvature (C), Lineament density (LD), Distance from drainage (Dfd), and land use land cover (LULC). As a result, establishing a connection between causative factors and landslides becomes both a critical and challenging thing.

AHP statistical analysis was applied for the mapping of landslide susceptibility, which may be taken into account in expert opinion methods. In general, the following actions are necessary to complete AHP: A difficult, unorganised issue should be broken down into its constituent parts in the following steps: (1) to set up the elements in a hierarchy; (2) to assign numerical numbers to arbitrary assessments of each factor's relative relevance; (3) to allocate the assessments to establish these aspects' relative priority; and (4) to analyse the judgements. The third stage in this technique has likely generated the greatest discussion because it includes subjectivity in its broad form. Making judgements based on a hierarchical arrangement of the elements is what this entails when dealing with complicated issues. Pairwise comparisons of the controlling elements are used in a semi-qualitative procedure to give them weightage values ranging from 1 to 9 [6]. In Table 1, the factor classes are given the standard scale for pairwise comparisons, and the factors are assessed about one another. Pairwise comparisons of the controlling elements are used in a semi-qualitative procedure to give them weightage values ranging from 1 to 9 [6]. In Table 1, the factor classes are given the standard scale for pairwise comparisons, and the factors are assessed about one another:

Problems with decision-making need support from a wide range of possible circumstances. Better decisions may result from giving the affecting elements the proper importance. The best results might be obtained using multi-criteria assessment,

which takes into account a variety of important factors, if proper weighting are used. The structure-based decision-making method known as AHP was developed by Saaty in 1980. It employs a simple mathematical model to address complex decision-making problems. Researchers have been impressed with AHP's capacity to give input components the ideal weights and provide outputs like landslide susceptibility mapping. The AHP concept is based on the correlative relevance of components specified on a scale of priority. This technique gives fair weights to the components that are being evaluated because of its distinctive consistency test.

Creation of a hierarchy and relative evaluation of components based on relevance versus purpose, weighting calculations for each element, computation of consistency vector (CV), computation of average value of CV and consistency index (CI), selection of random consistency index (RI) regarding a number of variables, calculation of consistency ratio (CR), comparison of CR with $CR_{\text{threshold}}$ to determine suitability are subsequent steps of the implementation of AHP.

Table I. According T.L. Saaty (1994), the Linguistic scale of factors comparison as per their importance

1	Equal importance
3	Moderate importance
5	Strong importance
7	Very strong importance
9	Extremely strong importance
2,4,6,8	Intermediate importance

Table II. RI and CR values are based on the numbers of included n factors (Saaty 1994).

N	3	4	5	6	7	8
Random consistency Index(RI)	0.58	0.9	1.12	1.24	1.32	1.41
Consistency ratio (CR)	0.05	0.08	0.1	0.5	0.1	0.1

In this research, the parametric pairwise matrices were filled using an expert's judgement. Using the AHP tool in GIS software, this table was created. Based on this a susceptibility map will be generated. The first step is to build a pairwise comparison matrix (PCM) based on the significance of each input component in relation to other possible factors (Table 3).

The weights of each element for the PCM of n factors described by “(1)” might be determined as given in “(2)”. The suggested PCM is assessed using a consistency check using CV (Equation (3))

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \cdots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix} \quad (1)$$

$$W = \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{bmatrix} = \begin{bmatrix} \frac{a_{1j}}{\sum_{j=1}^n a_{1j}} \\ \frac{a_{2j}}{\sum_{j=1}^n a_{2j}} \\ \vdots \\ \frac{a_{nj}}{\sum_{j=1}^n a_{nj}} \end{bmatrix} \quad (2)$$

$$CV = \begin{bmatrix} \frac{\sum_{j=1}^n a_{1j} \times w_j}{w_1} \\ \frac{\sum_{j=1}^n a_{2j} \times w_j}{w_2} \\ \vdots \\ \frac{\sum_{j=1}^n a_{nj} \times w_j}{w_n} \end{bmatrix} \quad (3)$$

To check for consistency, CR is computed in the end.

$$CR = \frac{CI}{RI} \quad (4)$$

Where CI is determined by aggregating CV values and PCM is used for calculating RI.

$$CI = \frac{\lambda - n}{n - 1} \quad (5)$$

The proposed PCM is rejected and the relative weights of the included criteria are re-evaluated if CR (a measure of acceptance of any proposed PCM) is greater than a certain threshold. The assigned weights are regarded as accurate and acceptable if CR is less than the threshold, as indicated in Table 4.

The selection of elements that should be incorporated into susceptibility mapping and the determination of priority, or relative relevance, amongst components, are both necessary for the execution of AHP. The likelihood of receiving inconsistent findings is higher. Therefore, it is advised to conduct many trials to hit the CR (threshold) and obtain reasonable results. Consequently, an expert recommendation might simplify this procedure. It was impossible to overlook the idea that various groups may use the same parameters for a research location and come up with different outcomes. This is such that the threshold value, which is made achievable by modified PCMs, permits CR to be less than 10%.

Table III. comparison matrix for seven parameters

	L	A	S	C	LD	DfD	LULC
L	1	2	3	4	7	8	9
A	1/2	1	1/2	3	5	8	5
S	1/3	2	1	2	3	8	5
C	1/4	1/3	1/2	1	1	3	8
LD	1/7	1/5	1/3	1	1	5	4
DfD	1/8	1/8	1/8	1/3	1/5	1	1
LULC	1/9	1/5	1/5	1/2	1/4	1	1

All the values present in a cell of Table III gets divided by the sum of that column. This gives the criterion weights and was shown in Table IV.

Table IV. Criterion weights

	L	A	S	C	LD	Dfd	LULC	Sum	weights
L	0.41	0.34	0.53	0.35	0.4	0.24	0.27	2.54	0.36
A	0.2	0.17	0.09	0.26	0.29	0.24	0.15	1.4	0.2
S	0.14	0.34	0.18	0.17	0.17	0.24	0.15	1.39	0.2
C	0.1	0.06	0.09	0.09	0.06	0.09	0.24	0.72	0.1
LD	0.06	0.03	0.06	0.09	0.06	0.15	0.12	0.56	0.08
Dfd	0.05	0.02	0.02	0.03	0.01	0.03	0.03	0.19	0.03
LULC	0.05	0.03	0.04	0.01	0.01	0.03	0.03	0.2	0.03

Using “(2)” The weights (W) of all the parameters was calculated. The weightage for each factors calculated by using AHP.

$$\begin{aligned}
 W &= \begin{matrix} w_1 & 0.375503 \\ w_2 & 0.206319 \\ w_3 & 0.2048 \\ w_4 & 0.079411 \\ w_5 & 0.073344 \\ w_6 & 0.027174 \\ w_7 & 0.033449 \end{matrix}
 \end{aligned}$$

Table V. Check the consistency
Note: AoL=Average of Lambda

	L	A	S	C	LD	Df D	LUL C	WS V	W	Lamb da = WSV/ W	AoL
W	0.36	0.2	0.2	0.1	0.08	0.03	0.03	-	-	-	-
L	1	2	3	4	7	8	9	2.83	0.36	7.81	7.61
A	0.5	1	0.5	3	5	8	5	1.57	0.2	7.86	
S	0.33	2	1	2	3	8	5	1.55	0.2	7.82	
C	0.25	0.33	0.5	1	1	3	8	0.77	0.1	7.43	
LD	0.14	0.2	0.33	1	1	5	4	0.61	0.08	7.55	
Dfd	0.13	0.13	0.13	0.33	0.2	1	1	0.22	0.03	7.35	
LULC	0.11	0.2	0.2	0.13	0.25	1	1	0.21	0.03	7.45	

Using “(3)”, weighted sum value (WSV) was being calculated, in which the sum of the product of parameter to the weights.

$$CI = (7.61-7)/(7-1) = 0.102$$

$$CR - CI/RI = 0.102/1.32 = 0.07$$

Weights are considered appropriate if the CR value is below 0.10. Reassess the pairwise comparison if the CR value is higher than 0.10.

$$\begin{aligned}
 LSI &= [(Lithology \text{ map} * 2.83) + (Aspect \text{ map} * 1.57) \\
 &+ (Slope * 1.55) + (Curvature \text{ map} * 0.77) + \\
 &(Lineament \text{ density map} * 0.61) + (Distance \text{ from} \\
 &drainage \text{ map} * 0.22) + (LULC \text{ map} * 0.21)]
 \end{aligned}$$

In order to create the Landslide Susceptibility Index (LSI) map, the weighted sum values obtained by AHP were assigned as weight values to the classes of each component map using the raster calculator tool in ArcGIS. To produce the LSI, the total overlapped pixels for each pixel are added.

V. Result

In the current study, Rudraprayag comprising around 1984 sq. km is situated in the lesser Himalayan area was analysed for its vulnerability to landslides. In the research region, landslides were mapped in a total of 300. The AHP model was essentially taken into consideration for determining landslide vulnerability. In this study, the range from 0 to one was divided into four classes using a natural break division technique to reflect geographic differences in LSI. The lesser values indicate less hazardous zones and higher values indicate very hazardous zones. The Relative Operating Characteristics (ROC) module has been used for validating the generated landslide susceptibility maps. This module compares a suitable image indicating the probability of a class and a Boolean image indicating where that class really occurs to determine if a model's prediction of the place of its occurrence is accurate.

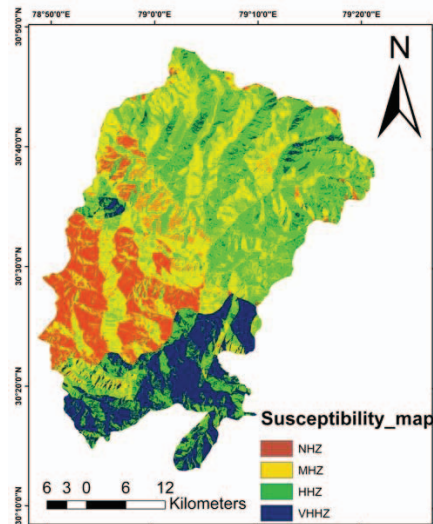


Fig. 2 Landslide Susceptibility Map Using AHP Model

VI. Validation of Results

The module uses the supplied threshold to calculate the area under curve (AUC) value. While a score of 0.5 represents the agreement that would be anticipated by chance, a value of 1 denotes full spatial agreement between the reference picture and the input image. The true-positive (TP)% and false-positive (FP)% values for each threshold that make up the curve from which the AUC is determined are likewise generated by the ROC module.

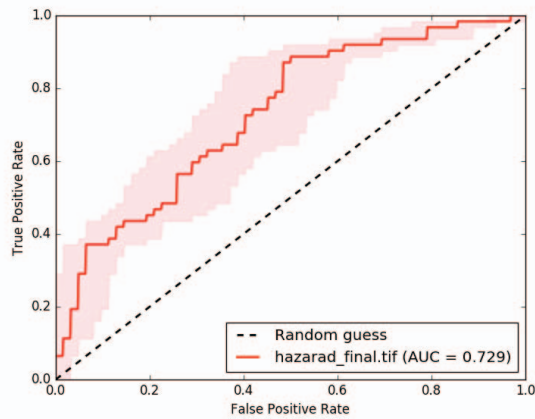


Fig. 3 Prediction rate curve for the susceptibility map produced in the study.

VII. Conclusion

The AHP is an expert-judgment heuristic approach with the ability to verify the consistency of the expert's rating. Because there are no discrepancies in this approach, it is correct for mapping LSI. Additionally, additional research sites with comparable geological, geomorphological, and hydro-climatic circumstances may apply the rating values provided in this study. AHP models often include a rating system that is based on the advice of experts. In fact, consulting an expert is often helpful in resolving difficult issues like landslides. But to a certain degree, opinions might vary depending on the particular professional and can thus be vulnerable to subjectivity and cognitive constraints. The lithology, aspect, slope, curvature, lineament density, distance from drainage, and land use land cover were the 7 causal parameters taken into account in this study. These 7 variables were chosen based on the data that were available for the research region and their applicability to landslide occurrences. However, given the availability of data for more research, more variables can be taken into account.

Policymakers, planners, and engineers may find the landslip susceptibility map offered in this paper to be a useful resource. This map offers useful information that may be used to focus attention on the vulnerable zones so that development can be done in those areas.

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