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Spatial Prediction of Landslide Hazard using GIS-multi-criteria Decision Analysis in Kullu District of Himachal Pradesh, India

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Abstract

The GIS-multi-criteria decision analysis (MCDA) techniques are increasingly used in landslide susceptibility mapping for predicting the future hazards, land use planning, and hazard preparedness. Identification of landslide susceptible regions helps in making a strategic plan for future developmental activities in the landslide-prone areas. It enables the integration of different data layers with varying levels of uncertainty. In this work, GIS-MCDA is applied to landslide hazard zonation for the Kullu district in Himachal Pradesh, India. The current work aims to evaluate the performance of the analytical hierarchy process (AHP) for the development of a landslide hazard map. The geographical information system is used for the preparation of the database, analysis, modelling, and results. The ArcGIS 10.0 software is used to integrate the input layers by assigning appropriate weights. Six landslide causal factors are used, whereby the parameters are extracted from an associated spatial database. These factors are evaluated, and then the respective factor weight and class weight are assigned to each one of the associated factors. The developed landslide hazard map is categorized into three risk zones. The current work may be of great assistance to regional planners and decision-makers in deciding on the most suitable risk mitigation measures at the local level to prevent the potential losses and damages from landslides in the region.

1. Introduction

Landslides are regarded as the primary mass loss process in mountainous terrain. Landslide hazards caused by geological, meteorological, and human-made variables put the lives and property of those who live in high terrain at constant risk. One of the geo-processes that is increasingly posing a significant environmental challenge to development efforts generally and in the Himachal Himalayas, in particular, is the risk of landslides. Thus it is anticipated that the frequency of landslides and losses caused by such hazards will continue to rise in the future due to the continuous urban and rural expansion, the current infrastructure development, and the current deficient landslide management system [1]. Landslides are described as a broad spectrum of geo-technical events that occur under the gravity's influence. A landslide is a form of mass wasting activity that refers to any outward or downslope movement of soil and rock caused by gravity when the drive surpasses the slope's resisting force. As a geological hazard, landslides are produced by earthquakes or eruptions, rainfall, and human action. When a part of a hill slope or a sloping section of the bottom becomes too weak to maintain its weight, a landslide occurs [2]. Landslides are often categorized according to the materials involved (rocks, debris, and soils) as well as the mechanism and failure mode. Groundwater content, as well as the velocity and size of the flow, are other important causative factors that contribute to landslide events. It is critical to classify and research this phenomenon to manage landslide damage. Landslides are characterized

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according to the method of movement, kinds of material, landslide activity, depth, rate of movement, size of the slide, and moisture content [1]. Landslides are common in the Kullu district due to strong Monsoonal rains and steep slopes. The only way to reduce the impact of a landslide is to have a thorough understanding of the likelihood of occurrence, type, and severity of a landslide in a given region. As a result, identifying the landslide-prone areas is critical for implementing safer mitigation measures and long-term planning in the area. Using geographical information system, the current work executes a landslide hazard zone in the western Himalayas in the district of Kullu in Himachal Pradesh. The goal of identifying landslide-prone regions is to increase the town's tourism value, and it will aid in reducing natural hazards that cause significant harm to life and property. Location, size, sliding mechanics, composition, velocity, and travel distance are all features of landslides. Based on the estimated relevance of causative variables such as instability, a landslide hazard zonation map divides the ground surface into zones with various degrees of stability.

Susceptibility/vulnerability, hazard, and risk mapping are the most essential tasks in geo-hazard mapping for understanding, mapping, and assessing the spatiotemporal state and risk level due to geo-hazards. Susceptibility refers to the likelihood of an event of a certain kind occurring at a specific place, whereas hazard refers to the likelihood of an event of a specific type and size occurring at a specific location within a reference period. The assessment of landslide conditioning and triggering variables is a critical effort in hazard mitigation [3]. Several studies have been found in the literature relevant to the identification of landslide causative factors under various environmental conditions [4-10]. Structural alterations and singularities within the rock mass, as well as sudden variations in the strata's dip, suggest heterogeneities that might lead to collapse. Changes in the initial circumstances during excavation such as the presence of tectonic in situ stress due to compressive or extensional features like folds and faults might potentially affect slope stability. The current work adds to our understanding of landslide hazard mapping, which can aid the governments in landslide prevention and mitigation efforts.

2. Methodology and studied area

GIS and remote sensing techniques were used to map landslide zonation in this work. GIS is a quick and accurate approach that incorporates landslide triggering, variables that may be used to forecast the susceptibility of a landslide-prone area [11, 12]. In this work, GIS along with the analytical hierarchy process (AHP) is used for landslide hazard zonation. With the help of GIS-based MCDA techniques, the study's causative components have been modelled, weighted, and delineated in dangerous zones. The optimal and ranking methods are used to execute a multi-criteria evaluation, and the criteria are defined based on alternative, value, and weighted criteria.

The AHP method has been used to calculate the weights of landslide influence parameters. The parameters used in this studied area were IRS 1D LISS III imagery, topographic maps, geological maps, and soil maps. GIS has been used for the preparation of databases, analysis, modelling, and output. IRS 1D LISS III has been used for land-use/land cover maps. The Arc GIS 10.0 software has been used to integrate the input layers after assigning the appropriate weights. In addition to this, the studied area was along the national highway that connects the Kullu valley with the rest of the country. The entire inflow of tourists from various parts of the country is diverted to the valley during the tourist season leading to heavy vehicular traffic on this highway from the beginning of May until the end of October. This highway has its additional importance as the supplies of defence equipment and essential commodities for defence personnel deployed at Leh have been diverted through this route. Military vehicles carry supplies of essential commodities and defence equipment to the border parts of Leh from Pathankot and Chandigarh from the beginning of July and remain plying on this route to passes at “Rohtang” and “Baralacha”.

AHP is a multi-criteria, multi-objective decision-making technique in which the user gives a preference among several landslide-related factors through comparative judgment, decomposition, and combining of priorities. This technique was created in 1970 to give decision-making judgment based on the user's experience, while the structure's heuristics were based on the principles of knowledge. It follows a pairwise comparison matrix for comparing each landslide component [6]. In this method, each layer is split into small variables in this technique, and further, these minor elements were compared based on their relevance. Every class is weighted against each other for assessing class importance compared to each other by providing a comparative dominating value between 1 and 9 to each class [13].

When comparing the two elements, point 1 indicates that they are of equal significance, whereas point 9 indicates that a row component is more significant than the equivalent column factor, as shown in Table 1. The following components of level and their weights were used to create a pairwise comparison matrix as per Table 2: individual variables and their respective weights were shown: $A_1, A_2 \ldots A_n$, and $w_1, w_2, \ldots w_n$. The relative importance of a_i and a_j is denoted as a_{ij}, while the pair-wise comparison matrix of factors $A_1, A_2 \ldots A_n$ as $A= [a_{ij}]$ is expressed as:

$$A = \left[a_{ij}\right]_{n \times n} = \begin{pmatrix} 1 & a_{12} \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} \cdots & 1 \end{pmatrix} = \begin{pmatrix} 1 & \frac{w_1}{w_2} \cdots & \frac{w_1}{w_n} \\ \frac{w_2}{w_1} & 1 \ldots & \frac{w_2}{w_n} \\ \frac{w_n}{w_1} & \frac{w_n}{w_2} & 1 \end{pmatrix} \quad (1)$$

$a_{ij} = 1/a_{ji,}$ and consequently, when i is equal to j and a_{ij} is equal to 1. The final matrix was normalized using Equation 2 as:

$$a_{ij} = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}} \quad (2)$$

where i, j = 1, 2, …, n

In the final stage, the weight of factors was computed using Equation 3 as:

$$W_i = (1/n)\,(1/n) \sum_{i=1}^{n} a'_{ij} \quad (3)$$

If the horizontal axis factor is more significant than the vertical axis factor, the value ranges between 1 and 9, and if the horizontal axis factor is more essential than the vertical axis factor, the value changes between 1/2 and 1/9. The weight factors in the form of eigenvectors are obtained by calculating the matrix, as shown in Table 3. Calculating the eigenvalue is a necessary element of the AHP model. The comparison matrix's principal eigenvalue matching normalized right eigenvector indicates the relative relevance of the compared criteria. One of the key aspects of the AHP method is the computation of consistency index (CI) and consistency ratio (CR) [14]. The consistency index was calculated as follows:

$$CI = \lambda_{max} - N/(N-1) \quad (4)$$

Here, λmax = maximum principal eigenvalue of the matrix

N = number of elements present in the matrix

By multiplying the consistency index (CI) by the average random consistency index, the consistency ratio (CR) is computed (RI). Equation 5 calculates the consistency ratio as:

$$CR = CI/RI \quad (5)$$

The weights and their rating of landslide influence factors have been shown in Table 4. The lowest weight indicates low landslides and the higher weight indicates high landslides.

Table 1. Scale for pair-wise comparison.

Intensity of importance	Definition
1	Equal importance
2	Equal to moderate importance
3	Moderate importance
4	Moderate to strong importance
5	Strong importance
6	Strong to very strong importance
7	Very strong importance
8	Very to extremely strong importance
9	Extreme importance

Table 1. Pairwise comparison matrix.

Causative factors	Slope	Drainage density	Lithology	Landuse/Landcover	Soil	Aspect
Slope	1	2	3	3	9	9
Drainage Density	1/2	1	3	3	8	9
Lithology	1/3	1/3	1	2	4	5
Landuse/ Landcover	1/3	1/3	1/2	1	3	4
Soil	1/9	1/8	1/4	1/3	1	4
Aspect	1/9	1/9	1/5	1/4	1/4	1

Table 2. Factor and weights.

Sr. No.	Factor	Weighted by pair-wise comparison
1	Slope	38.1
2	Drainage density	29.6
3	Lithology	14.4
4	Landuse/Landcover	10.4
5	Soil	4.9
6	Aspect	2.7

Table 3. Weight's rating scheme for factors and their classes.

Factor	Classes	Rating	Weight
Slope	0-15	1	38.1
	15-25	3	
	25-35	5	
	35-45	7	
	> 45	9	
Aspect	Flat	0	2.7
	North	1	
	North east	4	
	East	7	
	South east	8	
	South	9	
	South west	6	
	West	3	
	North west	2	
Landuse/Landcover	Moderate cover forest	5	10.4
	Sparsely vegetative land cover	9	
	Water body	0	
	Agricultural & inhibited land	1	
	Snow covered area	9	
	Barren land	7	
	Rock outcrop	5	
Drainage density	Low	1	29.6
	Medium	5	
	High	9	
Soil	Sandy	7	4.9
	Sandy with loamy	6	
	Loamy	5	
	Calcareous loamy	7	
	Course loamy	6	
Lithology	Assorted material	5	14.4
	Granotoid gneiss	3	
	Slate with quartzite	2	
	Schist	4	

A consistency ratio of 0.10 or less indicates a reasonable level of consistency in pair-wise comparisons; if the consistency ratio is greater than 0.10, the values of the ratio are indicative of inconsistency judgment. The consistency ratio for the weights was calculated using the AHP technique.

The studied area was traced in and around the Kullu town of Himachal Pradesh, as shown in Figure 1. It falls from 32°00'00" to 32°30'00" Northern latitude and from 77°00'00" to 77°30'00" Eastern longitude with a respective topological map, as shown in Figure 2; IRS-1D LISS-III digital elevation was used for the development of thematic layers, as shown in Figure 3.

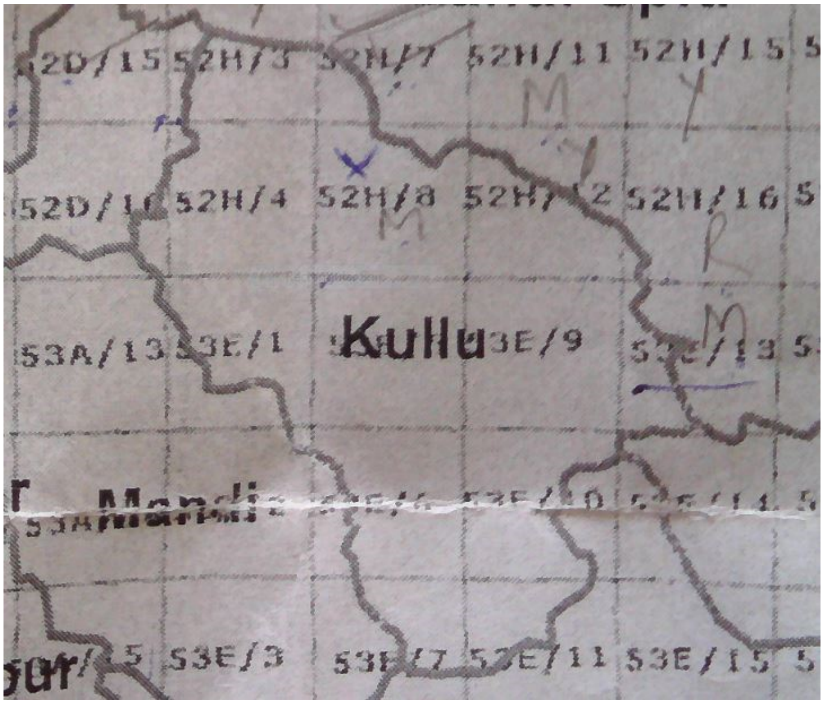

Figure 1. Topological sheets numbers in which area lies (52H/3, 52H/4, 52H/7, and 52H/8).

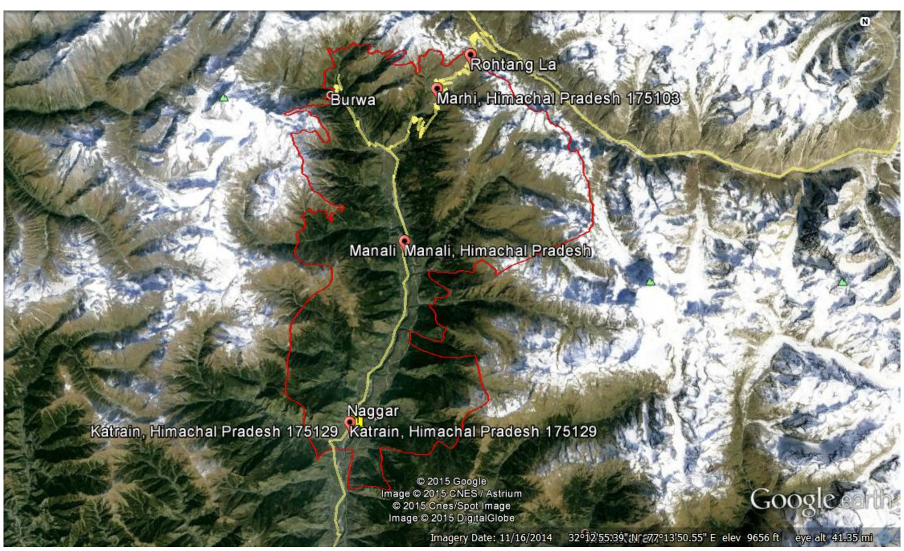

Figure 2. Google earth image showing location of studied area.

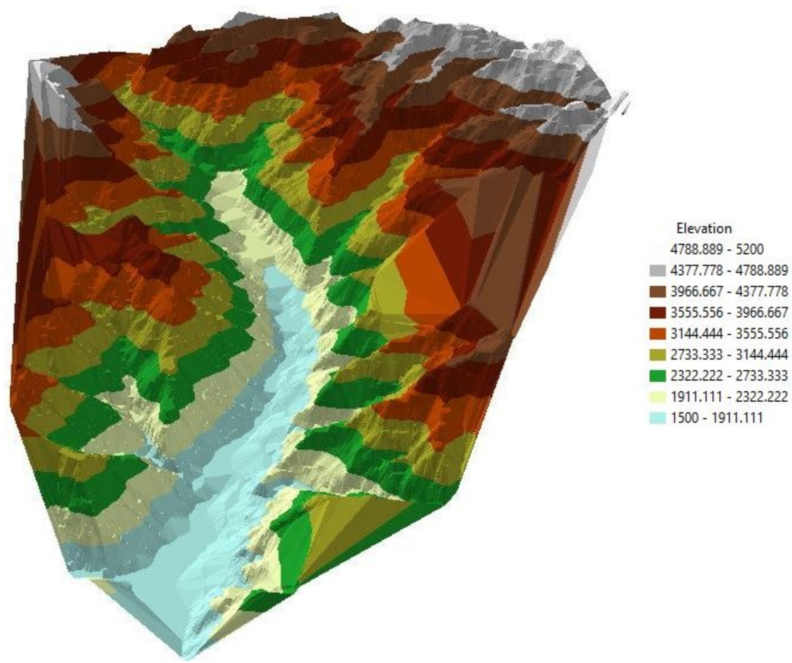

Figure 3. IRS-1D LISS 3 DEM data.

3. Results and discussion

The present work concluded six parameters: slope, drainage density, lithology, land use, soil, and aspect for the development of landslide hazard zonation map. These were selected for assessing the relative importance of the selected causative factors. This has been done by pair-wise comparison of each pair of parameters using the GIS-MCDA approach.

3.1. Slope and aspect

Slope and aspect are the major determinants of an area's hardiness. The rate of change in elevation over distance is referred to as slope degree, with greater slope values indicating steeper terrain and lower slope values indicating flatter terrain. The aspect determines the direction of the steepest slope or the downslope direction of the maximum rate of change [15, 16]. Gentle slopes (below 20°) make up roughly a third (34.25%) of the entire area of the Kullu district, and can be found either along the river's course or on ridge tops. Moderately steep and steep slopes account for 35.35% and 24.55% of the total area, respectively; very steep to precipitous (over 40°) slopes account for around 6% of the entire area. The district's aspect distribution was traced as even, with all nine directions accounting for 10-15% of the total area. Generally, slopes from the southeast (SE) to the south (S) and southwest (SW) are thought to be more prone to slope collapse and sliding activity. In the studied area, the slope has been classified into 5 classes, 0-15°, 15-25°, 25-35°, 35-45°, and >45°, as shown in Figure 4 (a). The rating has been given on a 0-9 scale based on the degrees of slope. On the other hand, the aspect tool in GIS was used to create an aspect map. It refers to the direction of the terrain surface's maximum slope [17]. The aspect, which was formed as a result of the stability of the slope, depicts a direction from 0° to 360°. The aspect values have been categorized into nine direction classes, namely N, NE, E, SE, S, SW, W, NW, and flat, as shown in the Figure 4.(b).

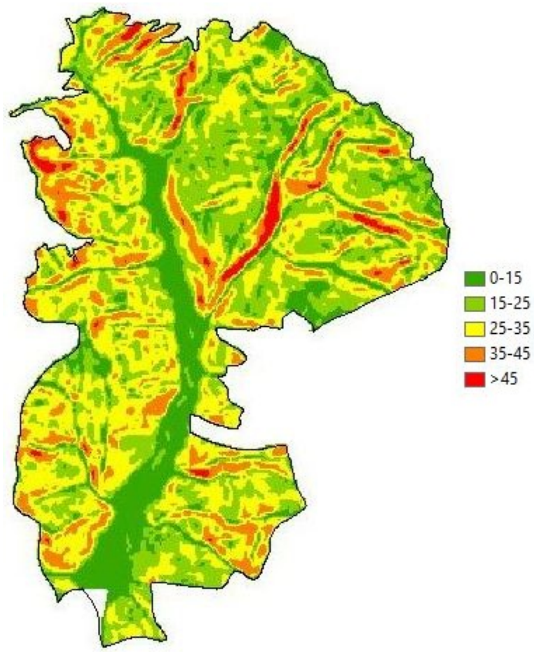

Figure 4 (a). Slope degree map.

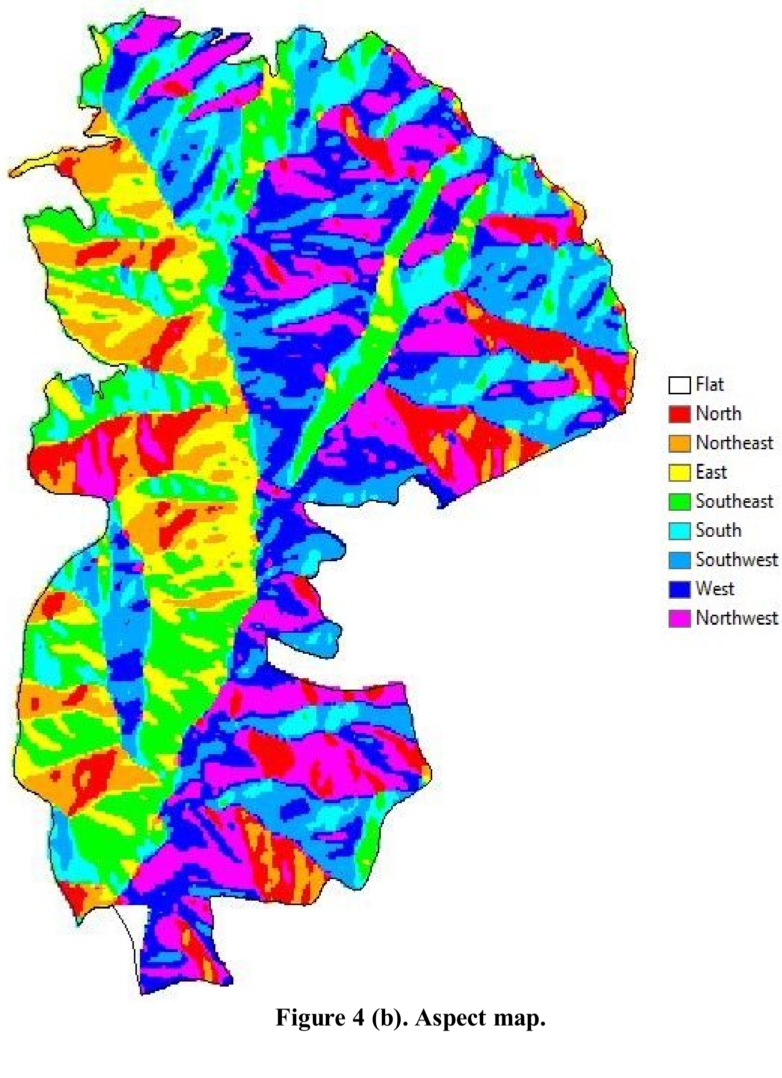

Figure 4 (b). Aspect map.

3.2. Physiography and relief

The studied area has a lot of relative relief, which is the difference in altitude between the highest and lowest points in a given area. Higher numbers imply a quick rise in altitude and the existence of faults, while lower values depict mature topography. Relative relief plays an important role in shaping the morphological character of an area by functioning as a triggering element for landslides. Relative relief significantly impacts the vulnerability of settlements and transportation networks. In Figure. 4(c), a wide range of relative relief has been traced in the current studied area, ranging from low to very high.

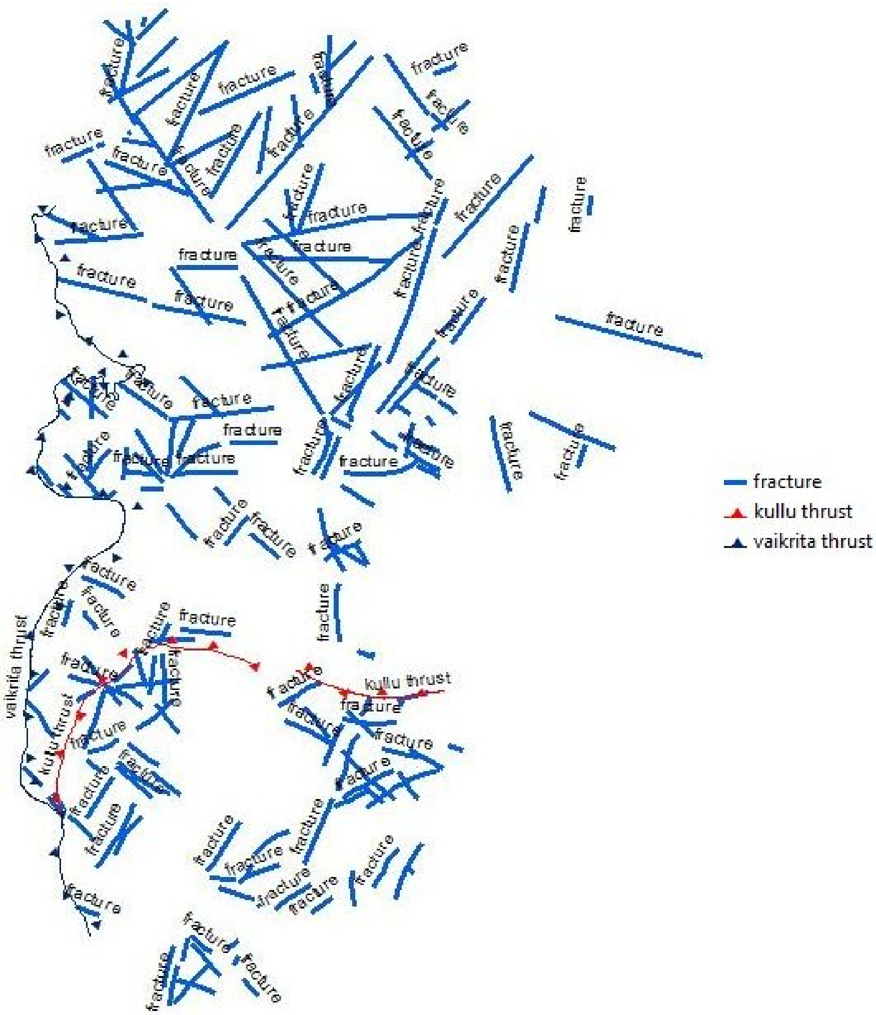

Figure 4 (c). Structural map.

3.3. Geological structure

The Himalayan axis is formed by a large core zone of crystalline unfossiliferous rocks such as granite, gneisses, schist, and other metamorphic rocks. The geology of the contemporary area was expressed by five major litho-tectonic units: (1) Vaikrita Group (2) Jutog Group (3) Kullu Group (4) Larji Group, and (5) Rampur Group. Several large thrusts including the Jutogh Thrust, Kullu Thrust, and Vaikrita Thrust, as well as several minor faults/lineaments, crosses the area. These thrusts are still active, and play an important role in the region's neotectonics [18]. The Kullu group and the Jutogh group were separated by the Jutogh thrust, whereas the Rampur-Larji group and the Kullu group were separated by the Kullu thrust or Chail thrust [19]. The Kullu Valley is primarily a gently folded anti-form with the river Beas following its axial plane along a fault running NNW-SSE from the upper watershed to around Aut, where it is intersected by a cross fault practically at right angles [20, 21]. This fault was a dextral tear fault with a 1.5 km dislocation [14], as shown in Figure 4 (d). A lithological/geological map was used to create the lithology map. It is also one of the most essential elements for landslide occurrence. Schist, slate with quartzite, granitoid gneiss, and miscellaneous material are among the four types of rocks found in the research region. The rock types were transformed into a raster format after being digitized as polygons. A rating has been assigned to rocks based on their vulnerability to landslides on a 0-9 scale, with 0 indicating no landslides and 9 indicating greater sensitivity to landslides.

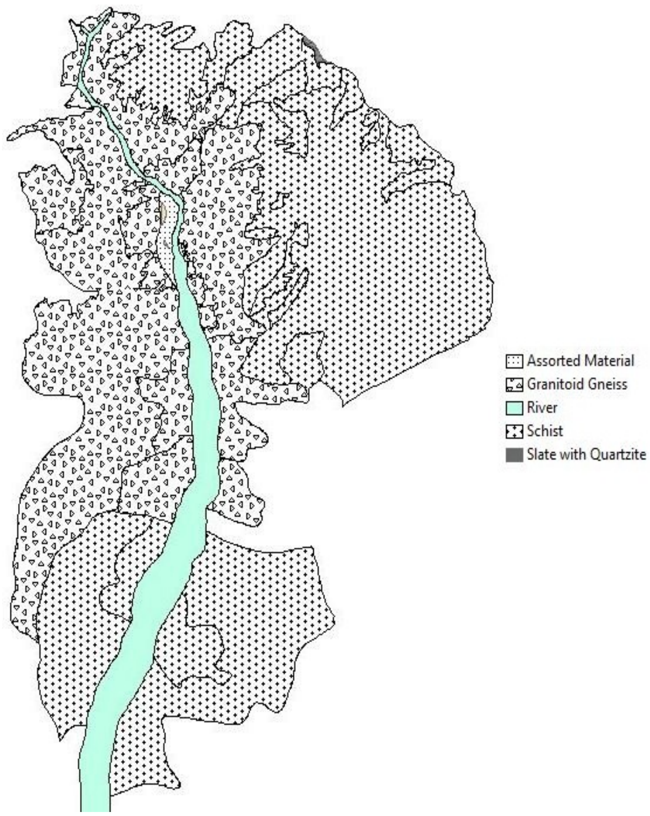

Figure 4 (d). Lithology map.

3.4. Drainage character

The studied area's drainage patterns are the result of a long-term interplay between the geological structure, topography, and slope. With obvious evidence of parallel dendritic and trellis patterns in between, the overall drainage indicates the early stage of the dendritic pattern as shown in Figure 4(e). Drainage density is important for defining landscape segmentation and runoff potential. Higher values indicate a greater degree of land dissection as well as a greater likelihood of slope failure. Topographic maps were used to create the drainage density map. As shown in Figure 4 (f), the drainage density was calculated using a 250-by-250-m cell, and was divided into low, medium, and high density. The drainage density map was superimposed on the drainage density map depicts that the high-density class has a greater number and closer spacing of drainage channels than the medium and low-density classes.

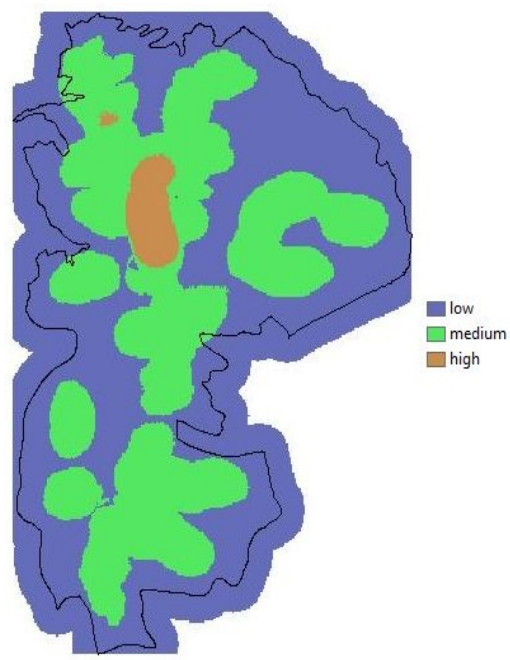

Figure 4 (e). Drainage map.

3.5. Soil

In identifying landslide-prone locations, the soil is thought to be the primary cause because it is crucial for slope stability [22-25]. The soil's thickness and cohesion have a significant impact on how quickly landslides spread. In the current studied area, the soil map was derived from Himachal Pradesh soil maps and the Land Use Planning and Agriculture Department of Himachal Pradesh. As indicated in Figure 4 (g), the soil in the area was classified as sandy, sandy with loamy, loamy, calcareous loamy, and course loamy. The soil types were digitized as polygons from a registered soil map and converted to raster; the rating was determined by the soil type's susceptibility to landslides.

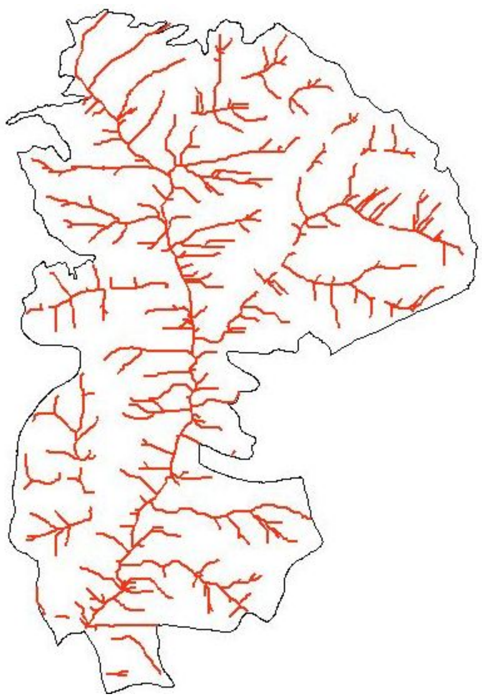

Figure 4 (f). Stream network.

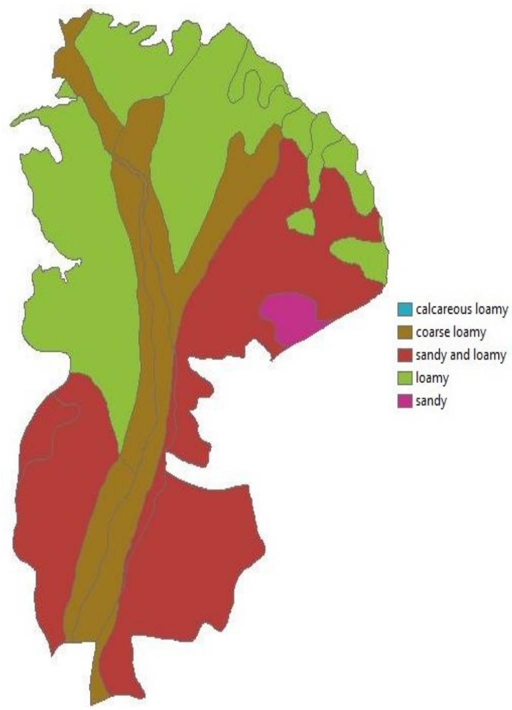

Figure 4 (g). Soil map.

3.6. Land use/land cover

Land use/land cover analysis examines the links between land use, catastrophe risk, and disaster vulnerability [26-28]. The present work adopted land use/land cover analysis based on IRS-1D LISS-III DEM. Landuse/landcover map has been developed by multisource image classification of LISS III image. The multisource image categorization of the LISS III picture resulted in the creation of a land use/landcover map. To lessen the effect of shadows cast by high mountain peaks in the studied area, multisource classification was used. In this work, seven classes were classified, as indicated in Figure 4 (h). Land use and land cover has been widely important in assessing landslide hazard and transportation system [29, 30]. Waterbody, moderately vegetative land cover, sparsely vegetative land cover, agricultural cum inhabited land, snow-covered area, barren land, and rock outcrop are the different types of land. To lessen the effect of shadows in the region and improve the difference between distinct classes, a digital elevation model (DEM) and a normalized difference vegetation index (NDVI) were added to the classification process.

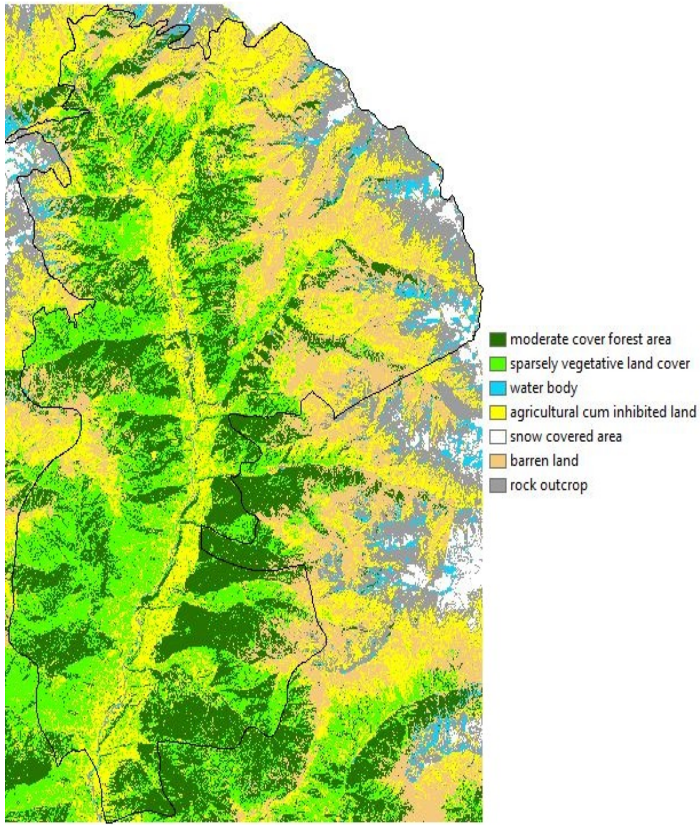

Figure 4 (h). Landuse/landcover map.

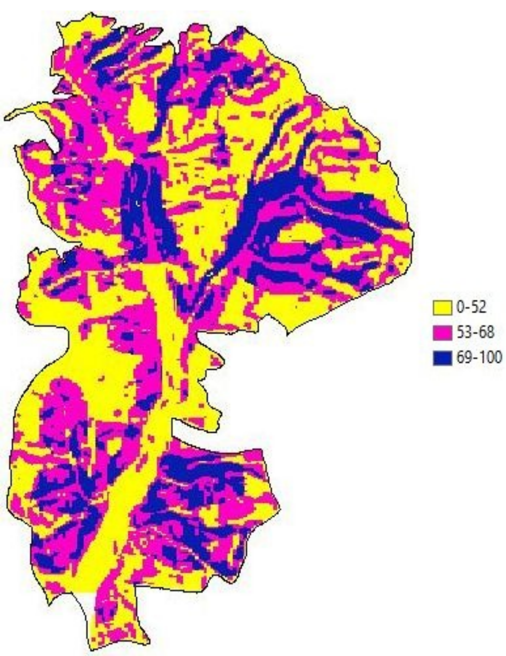

Figure 5. Final landslide hazard zonation map.

4. Conclusions

In India's middle Himalayan zones, landslides are the most dangerous natural hazards. In this work, GIS-multi-criteria decision-based AHP model was adopted to develop a landslide hazard map of the Kullu region in Himachal Pradesh. To achieve the current objective, six landslides influencing factors were considered, i.e. slope, aspect, land use/land cover, soil, drainage density, and lithology. Subsequently, the main causative factors were assessed, and then weights were attributed to each one of the considered factors. The present AHP model was built on a grading system based on expert judgment. It reveals as the best method due to its pair-wise comparisons of the causative factors that eliminate differences in the decision-making process. The final developed map was categorized into three classes i.e. low hazard, medium hazard, and high hazard zone of the landslide, as shown in Figure 5. The final developed map was divided into three zones, respectively, i.e. 0-52% low landslide hazard zone, 53-68% medium landslide hazard zone, and > 68% high landslide hazard zone. The developed GIS-MCDA model proved at an acceptable level because the developed LHZ map showed a 90% level of prediction accuracy when compared to the previous landslide inventory sites. This work will be useful for designing mitigation techniques in landslide-affected areas as well as for identifying places that should be avoided for buildings and areas that are more likely to experience sliding activities. The results of the GIS-MCDA approach are suitable for the zonation of the area's landslide hazards based on regular natural geographical features. Other research locations with similar geomorphological, geological, and hydro-geological conditions could use rating values given to various causative factors in the current study to map the landslide hazards.

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پیش بینی فضایی خطر زمین لغزش با استفاده از تجزیه و تحلیل تصمیم گیری چند معیاره GIS در منطقه کولو هیماچال پرادش، هند

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چکیده:

تکنیک‌های تحلیل تصمیم‌گیری چند معیاره (GIS (MCDA به طور فزاینده‌ای در نقشه‌برداری حساسیت زمین لغزش برای پیش‌بینی خطرات آینده، برنامه‌ریزی کاربری زمین و مواجه با خطر استفاده می‌شوند. شناسایی مناطق مستعد زمین لغزش به ایجاد یک برنامه استراتژیک برای فعالیت‌های توسعه‌ای آتی در مناطق مستعد لغزش زمین کمک می‌کند. این امکان ادغام لایه‌های مختلف داده با سطوح مختلف عدم قطعیت را فراهم می‌کند. در این کار، GIS-MCDA برای پهنه‌بندی خطر زمین لغزش برای ناحیه کولو در هیماچال پرادش، هند انجام شد. پژوهش پیش رو به ارزیابی عملکرد فرآیند تحلیل سلسله مراتبی (AHP) برای توسعه نقشه خطر زمین لغزش پرداخته است. سیستم اطلاعات جغرافیایی برای تهیه پایگاه داده، تجزیه و تحلیل، مدل سازی و نتایج استفاده می‌شود. نرم افزار ArcGIS 10.0 برای ادغام لایه‌های ورودی با اختصاص وزن‌های مناسب برای این پژوهش بکار گرفته شد. برای انجام این پژوهش از شش عامل مهم در زمین لغزش استفاده شده است و این پارامترها از یک پایگاه داده مرتبط استخراج شدند. این عوامل ارزیابی شده و سپس وزن عامل مربوطه و وزن کلاس به هر یک از عوامل مرتبط اختصاص داده می‌شود. نقشه خطر زمین لغزش تهیه شده در سه منطقه خطر طبقه بندی شده است. کار فعلی ممکن است کمک بزرگی به برنامه ریزان و تصمیم گیرندگان منطقه‌ای در تصمیم گیری در مورد مناسب‌ترین اقدامات کاهش خطر در سطح محلی برای جلوگیری از خسارات و خسارات احتمالی ناشی از رانش زمین در منطقه باشد.

کلمات کلیدی: خطر زمین لغزش، فرآیند تحلیل سلسله مراتبی، تصمیم گیری چند معیاره، سیستم اطلاعات جغرافیایی، پهنه بندی.