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INTEGRATING GEOSPATIAL ANALYSIS AND MULTI-CRITERIA DECISION-MAKING FOR LANDSLIDE RISK GOVERNANCE: A STEP TOWARDS LOCAL RESILIENCE AND SUSTAINABLE DEVELOPMENT

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Abstract
Landslides are one of the most devastating global hazards, resulting in significant loss of life, property, and infrastructure worldwide. Addressing landslide risks aligns with United Nations Sustainable Development Goals (SDGs), specifically aligned with SDG 11 (Sustainable Cities and Communities) and SDG 13 (Climate Action) by reducing disaster vulnerabilities. Himachal Pradesh is considered as one of the important hotspots when it comes to landslides, Shimla district has religious and tourism importance and is substantially affected by frequent landslides. The mapping and assessment of landslide susceptibility zones are crucial for disaster risk reduction, Government policies and land-use planning. This paper presents a comprehensive research methodology for landslide susceptibility mapping integrating Analytical Hierarchy Process - Geographic Information System approach. The AHP allows for the incorporation of expert judgment in the evaluation of various causative factors, while GIS facilitates the spatial analysis and visualization of the susceptibility zones. About nine landslide causative factors (geology, slope, rainfall, land-use landcover, drainage density, elevation, aspect, distance to road and curvature) were considered for the study and corresponding thematic maps were prepared which were utilized in final preparation of landslide susceptibility zonation mapping. Using AHP technique and pairwise comparison the weightages are assigned to thematic layers according to their prominence and dynamic processes in the study area. The research is conducted in a Shimla district which is known for its landslide activity, and the results demonstrate the effectiveness of the AHP-GIS approach in delineating landslide-prone areas. The findings depict valuable insights for decision-makers and stakeholders in developing strategies for landslide risk management and mitigation, contributing to sustainable land-use planning and disaster resilient development. The outcomes of this study provide valuable inputs for local self-government bodies to incorporate geospatial risk assessment into sustainable land-use planning and disaster management policies.

Keywords - Landslide Susceptibility Zonation, Analytical Hierarchy Process (AHP), Geospatial Technology, Multi-Criteria Decision Analysis (MCDA), Shimla District, Sustainable Development Goals (SDGs), GIS-based Hazard Mapping

Introduction

One natural phenomenon of earth crust is landslides, which occur due to the earth's gravitational movements, rock and debris along a slope. They pose a serious risk to human lives, infrastructure and environment. One of the most important tools for identifying landslide-prone locations is landslide susceptibility mapping, hence making it possible to make risk assessments and management. One of the earliest frameworks proposed by Varnes (1984) to assess the landslide hazard zonation provided the conceptual basis of slope instabilities identification and classification. His masterpiece in research work is still a model of mapping hazards methodologies that is still used in the present studies of landslides. Anbalagan (1992) also presented a methodology approach that can be applied to the assessment of landslide hazards in steep mountainous terrain showing that geological and morphological aspects to be used jointly with land-use land-cover aspects to achieve reliable zonation. This model justifies the choice of factors in the current research.

The sustainability principles of engineering in landslide susceptibility mapping guarantees a long term environmental and socio-economic advantages. This research contributes to the sustainable infrastructure development (SDG:9, Industry, Innovation and Infrastructure) and ecosystem protection, as well as prevents ecosystem damage (SDG:15, Life on Land). These methodologies do not only help to eliminate immediate risks, but also promote dynamic land-use policies in accordance to the global sustainability models. Agenda 2030 of the United Nations (2015) highlights the contribution of risk minimization to disasters in the form of SDGs. The connection between hazard assessment and sustainability will ensure that research such as this one is accepted directly to the resilience of global climate and secure communities. In addition, Kwan and Chang (2021) analyzed strategies of landslide risk management within the framework of sustainable development and pointed out that risk reduction frameworks have to correspond to the environmental and socio-economic sustainability. This can be compared with the focus on engineering sustainability in the current study. Landslides prediction and prevention need the knowledge of what triggers its occurrence. The combination of AHP-GIS methodology has been a successful method towards landslide susceptibility mapping. Sarkar and Gupta (2005) examined several methods for landslide hazard zonation in India, especially in the Himalayas, and suggested integrating GIS and remote sensing with conventional field surveys. This gives the relevance of applying geospatial technologies in this study area. AHP is a multi-criteria decision making (MCDM) technique for systematic evaluation of various factors that contribute to landslides occurrence. Factors considered for current study includes geology, slope, rainfall, LULC, drainage density, elevation, aspect, distance to road and curvature.

Pachauri and Pant (1992) emphasized the importance of geological parameters in hazard mapping, showing that lithological units and structural weaknesses are critical determinants of landslide occurrence. This justifies the inclusion of geology as a primary factor in this research. Jensen (2000) outlined how remote sensing provides critical environmental information, including land-use land-cover (LULC), which is essential for landslide studies. A satellite imagery carried out LULC classification in this study. GIS would allow mapping of the susceptibility areas as it offers a platform on which the spatial analysis and visualization can be conducted. It integrates the data of the field data and the satellite imagery data to form different maps. Anderson and Richards (1987) emphasized the interplay between the geomorphological processes and the geotechnical stability. Their observations support the necessity to use an interdisciplinary approach to slope stability and susceptibility zonation. The present paper demonstrates the analysis to create landslide susceptibility zone map of Shimla district with the help of AHP and GIS. The paper by Heikkala (2006) is a review of applications of GIS-based multicriteria decision analysis, which reveals that it can be used to address spatial issues, such as hazard mapping. This offered the practice of AHP and GIS combination to zonate landslides. The objective is to identify the key landslide-causing elements, weight them using AHP, and then combine the weighted components in the GIS to construct a zonation of landslide susceptibility.

Study Area

The study was conducted in Shimla district of Himachal Pradesh, India, which is situated in the Himalayas (Fig. 1) which is quite familiar with the landslides. This area boasts of cultural value, tourist destination and major fruits exporter in the world. The complex topography of this region, diverse geology and climatic formations are some of the factors, which promote landslides.

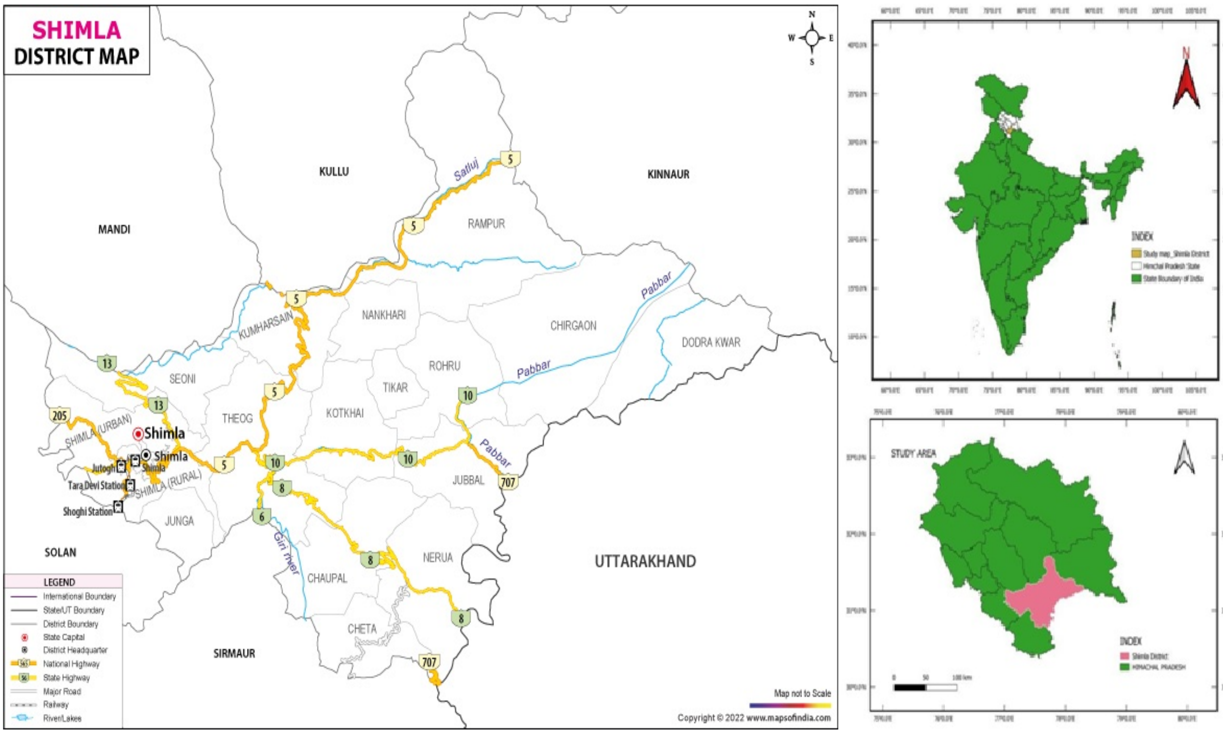

Fig. 1 Map of Shimla District

This district has been facing several landslides every year, and this has a drastic effect on the infrastructure, livelihood, road networks, tourist activities and the local ecosystems that have an impact on the economy of this district. The highly volatile geology of the Himalayas, and unplanned urbanization development, as well as deforestation, increases the susceptibility of this area. This choice of the area is informed by the availability of historical landslide information, the diversity of the region, and the potential of having AHP-GIS methodology. To prioritize the high-risk regions and direct the development of resilient infrastructure in Shimla, a thorough mapping of landslide susceptibility is of critical importance.

Methodology

The methodology adopted in this research integrates geospatial datasets with the AHP to produce a map of Shimla district's landslide susceptibility zonation (LSZ). The workflow consists of four major stages: (i) data collection and thematic layer preparation (ii) factor selection (iii) weighting of factors using AHP and (iv) GIS-based overlay analysis for susceptibility mapping and validation.

Data Collection and Thematic Layer Preparation

In recent times, the data from the satellite images has emerged as one of the important data for creation of various thematics layers in GIS. For this research study, various thematic layers such as geology, slope, rainfall, LULC, elevation, drainage density, aspect, distance to road and curvature are created using various satellite data and GIS software. According to Clarke (2003), GIS is a useful tool in managing spatial data and in modeling hazards, as it demonstrated its use in combining several thematic layers. The study area is used to produce the elevation, aspect, slope and curvature map using DEM. The DEM utilized was acquired on ISRO Bhonidhi's website. The DEM's spatial resolution of 30 meters is sufficient to provide the appropriate terrain parameters which include slope, aspect and elevation. This information served as one of the main sources of topographic and geospatial analysis that was conducted in the current study. The remaining satellite information as well as topography maps, geologic survey, and meteorological information is used to prepare LULC, geology, rain, drainage density and distance to road map. This paper used sentinel-2 satellite images to prepare

LULC map of the Shimla district. Because of the high spatial and spectral resolution of Sentinel-2 data, the data can make proper differentiation of various land cover classes and accordingly, it can be used in geospatial analysis on a detailed analysis. The data of the study on the average rainfall was taken at the India Meteorological Department (IMD). This data provides valid and reliable records of precipitation that was used to examine the spatial distribution of rainfall and its impact on environmental and geomorphological aspects of Shimla district.

The elevation, slope, aspect and curvature maps were calculated using topographic data of the Shuttle Radar Topography Mission (SRTM)-Digital Elevation Model (DEM) with a spatial resolution of 30 m. The Geological Survey of India (GSI) maps were used to collect the spatial analysis of geological data, which were georelated and digitized. The IMD obtained the rainfall data which acts as an average yearly precipitation. Surface information (LULC) was obtained on Sentinel-2 satellite images (12.5 m spatial resolution) through the supervised classification method. Topographic sheets by Survey of India (SOI) were also used to extract the drainage and road network data, which were improved with the help of OpenStreetMap (OSM) datasets.

Various datasets were used to create nine thematic layers that had an impact on landslides: geology, slope, rainfall, LULC, drainage density, elevation, aspect, distance to road and curvature. All data sets are converted to Universal Transverse Mercator (UTM) Zone 43N, and all data sets are resampled to even spatial resolution of 12.5 meters to provide consistency and provide good spatial overlay analysis.

Factor Selection and Criteria Justification

Nine causative factors (geology, slope, rainfall, LULC), drainage density, elevation, aspect, distance to road and curvature) were selected, as they have been well established in causation of slope instability and their usage supported by the previous literature (Varnes, 1984; Anbalagan, 1992; Guzzetti et al., 2005; Pourghasemi et al., 2012). The natural strength and resistance to weathering of the rock formations is controlled by geology, whereas the slope angle has a direct influence on the forces of gravity on materials. The rainfall serves as one of the controlling agents since it raises the pore-water pressure and decreases the shear strength. LULC identifies the runoff and infiltration patterns of the surface and this affects soil cohesion and erosion. The level of drainage density indicates the strength of the surface run-off and their erosive capacity. Micro-climatic factors such as elevation and aspect control, solar radiation, and vegetation cover which influence stability of the slope. Nearness to roads signifies human activities in the area in the forms of road cuts that tend to destabilize slopes. Curvature determines the concave and convex shape of the terrain, which determines the distribution of water and stress. All these nine factors are an embodiment of the geomorphological, hydrological, geological, and human factors of landslide susceptibility, which would give an intricate foundation of the reliable zonation mapping in Himalayan scenario.

Weighting of Factors Using AHP

In multi criteria decision making (MCDM) through AHP, a total of nine thematic maps are developed (Fig 2). The AHP that was developed by Saaty (1980) offers a mathematical model of the MCDM. It enables the comparison of factors one after another, and systematic calculation of weights which is the main part of the methodology used in this work. Subsequent improvements by Saaty (2008) also provided a greater boost to the reliability of AHP with the addition of consistency ratio checks to ensure subjective judgements are logically consistent. This is used to increase the strength of the assignment of factor weights in the process of creating susceptibility. Carras, Cardinali, and Guzzetti (1995) used GIS technology to map landslide hazard in digital spatial databases and overlay techniques are useful in enhancing susceptibility mapping. Their work is especially informative of the overlay analysis taken here. Nine factors were selected, namely, according to the literature review (Anbalagan, 1992; Van Westen, 1999; Pourghasemi et al., 2012) and expert advice. Natural breaks or thresholds of domain specific classification placed each thematic layer in a sub-class. Each class was assigned a relative rank (1–9) representing landslide favorability. The assigned weights as per their relative importance on Saaty's scale (1 to 9) are shown in Fig. 3. The pairwise comparison of the thematic layers was carried out using Saaty's Scale of relative importance presented in Table 1. This scale expresses the relative importance of one aspect over another in influencing landslide susceptibility by assigning numerical values (from 1 to 9). ArcGIS Pro (version 3.3.0) software was utilized for geospatial analysis and map preparation. The thematic layers shown in Fig. 2 were generated and analyzed using AHP to derive their respective weights. The Shimla district's Landslide Susceptibility Map (LSM), which has a spatial resolution of 12.5 meters, was created by integrating the weighted values using ArcGIS Pro's Weighted Overlay approach.

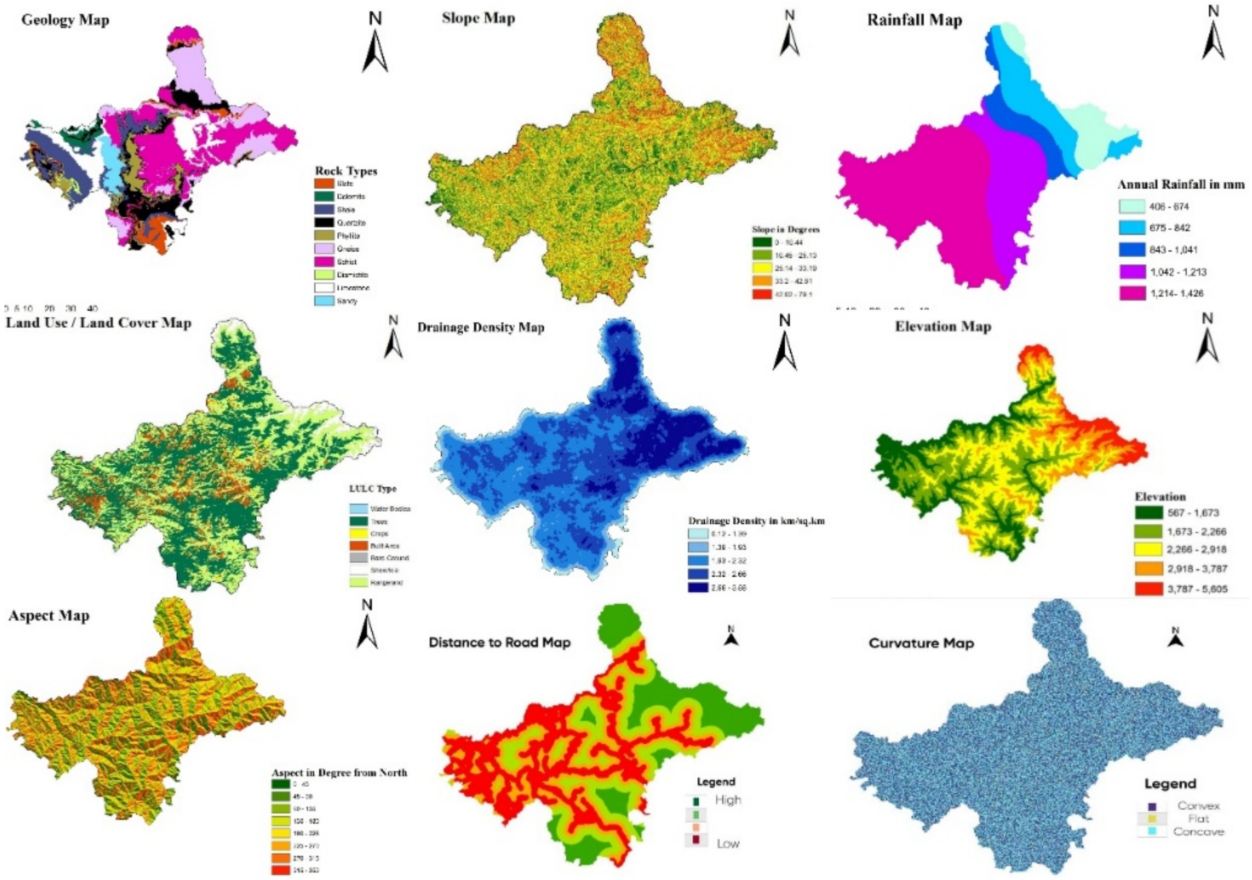

Fig. 2 Thematic Maps

Pairwise comparison is done for all nine thematic layers and a matrix is formed (Fig 3). Calculation of weight vectors is done using eigen vector analysis to calculate the weight of each factor. The AHP framework (Saaty, 1980; 2008) was applied to assign weights to the nine factors. Pairwise comparison matrices were developed based on expert judgement and literature evidence. Eigenvalue analysis was used to derive normalized weights. To ensure the perceptions are consistent, consistency check has been done by computing consistency ratio (CR) from eqn. 1. Consistency Index (CI) is calculated using eqn. 2. The Consistency Index (CI) and Consistency Ratio (CR) were computed (Saaty, 2008). A CR value of 0.09 indicated acceptable consistency (<0.1).

$$CR = CI / RCI \quad \ldots(1)$$

CI = Consistency Index and RCI = Random Consistency Index

$$CI = (\lambda max - n) / (n-1) \quad \ldots(2)$$

λmax = principle Eigen value,

n = number of criteria

	Geology	Slope	Rainfall	Landuse Landco	Drainage Densit	Elevation	Aspect	Distance to road	Curvature
Geology	1	3	5	6	6	7	6	8	4
Slope	1/3	1	3	4	5	6	7	7	5
Rainfall	1/5	1/3	1	2	3	4	5	6	3
Landuse Landcover	1/6	1/4	1/2	1	2	3	4	5	3
Drainage Density	1/6	1/5	1/3	1/2	1	2	2	3	2
Elevation	1/7	1/6	1/4	1/3	1/2	1	2	2	3
Aspect	1/6	1/7	1/5	1/4	1/2	1/2	1	2	2
Distance to road	1/8	1/7	1/6	1/5	1/3	1/2	1/2	1	1
Curvature	1/4	1/5	1/3	1/3	1/2	1/3	1/2	1	1

Fig. 3 Pairwise Comparison Matrix

GIS-based Landslide Susceptibility Mapping

AHP was developed by Thomas L. Satty to analyze decision making problems by allowing the calculation of inputs by a separate criterion of lower and higher hierarchies. There is a use of Satty's scale (1 to 9) to standardized the measurable and qualitative representation of input priorities.

The AHP-GIS approach not only enhances landslide prediction but also promotes sustainable decision making by balancing environmental, social and economic factors. This is corroborated by SDG 17 (Partnerships for the Goals) in terms of the incorporation of multidisciplinary data in assessing the risk holistically. Lee and Pradhan (2007) showed that statistical models such as frequency ratio and logistic regression are able to attain high accuracy of prediction as part of susceptibility mapping. The current AHP-GIS process is a supplement of such models that integrates the use of expert judgment and spatial analysis. Pradhan and Lee (2010) contrasted statistical and machine learning methods of zonation of land slides. Their results point to the fact that GIS structures are flexible and can be extended to suit various forms of modeling, such as the weighted overlay approach that is used in this study.

As mentioned above, the thematic layers have their weightages towards landslide susceptibility mapping as provided by Satty under Satty AHP. The comparison of the two is presented in the Figure 3. The diagonal elements in the matrix have all been maintained the same, that is, equal to 1. Eigen vectors are then calculated with the help of excel. In the case of nine layers, the RCI is assumed to be 1.45 (Table 2) and consistency ratio is 0.09 lower than the required value of 0.1. Therefore, it is necessary to make sure that pairwise matrix is consistent. A case study performed by Van Westen (1999) in the Andes using GIS to map susceptibility proved it to be effective in hazard zonation because of the effectiveness of the spatial data integration. This study is affirmative to his findings, which makes the GIS-based approach adopted justified. Van Westen, Castellanos and Kuriakose (2008) gave a summary of the spatial data needed to calculate the likelihood of landslides. Their emphasis on data quality and validation underlines the reliability of the results generated in the Shimla district.

Table 1 Satty's Scale

Intensity of Importance	Definition	Explanation
1	Equal importance	Two activities contribute equally
2	Equal to moderate importance	Experience and judgment slightly favor one activity over another
3	Moderate importance	

4	Moderate to strong importance	Experience and judgment slightly favor one activity over another
5	Strong importance	
6	Strong to very strong importance	The activity is favored very strongly over another, its dominance demonstrated in practice
7	Very strong importance	
8	Very strong to extremely strong importance	Evidences favoring one activity over another is of the highest possible order
9	Extremely strong importance	

Table 2 RCI values for different order of matrix

No. of criteria	1	2	3	4	5	6	7	8	9	10
RCI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.51

GIS Overlay Analysis

A tool available in GIS known as 'overlay analysis' is used to integrate the various nine thematic layers. This integration is done by utilizing a scale and ranks as per the importance of thematic layers to trigger a landslide. The thematic maps were integrated in ArcGIS using a weighted linear combination (WLC) approach. The landslide susceptibility index (LSI) for every pixel value was computed as:

$$LSI = \sum_{i=1}^{n} (W_i \times R_i)x$$

where W_i is the normalized weight of factor *i*, and R_i is the rank of its class. The final LSZ map was categorized into five susceptibility zones: very low, low, moderate, high, and very high.
The resultant of this overlay analysis in GIS software gives a landslide susceptibility map having five categories depicting very high, high, moderate, low and very low zones prone to landslide susceptibility (Fig 4).

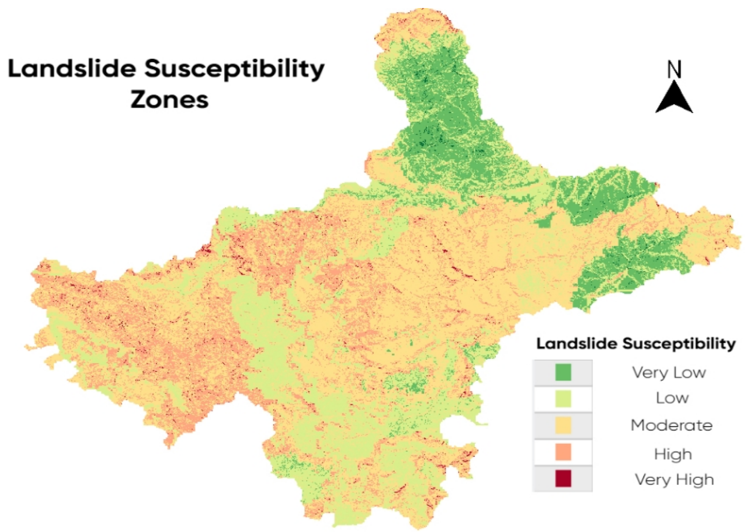

Fig. 4 Landslide Susceptibility Zone Map

The majority of Shimla district falls under moderate to low landslide susceptibility. The zones most susceptible to landslide are shown by red colour on the map. The Area Under Curve (AUC) of Receiver Operating Characteristics (ROC) analysis was used to compare the predicted susceptibility map with the real landslide events (Guzzetti et al., 2005; Lee and Pradhan, 2007). Validation of LSM was done using the ROC curve and the corresponding AUC values. These statistical variables are used to measure the predictive efficiency and performance of the susceptibility model by comparing the predicted areas of susceptibility with the actual landslides.

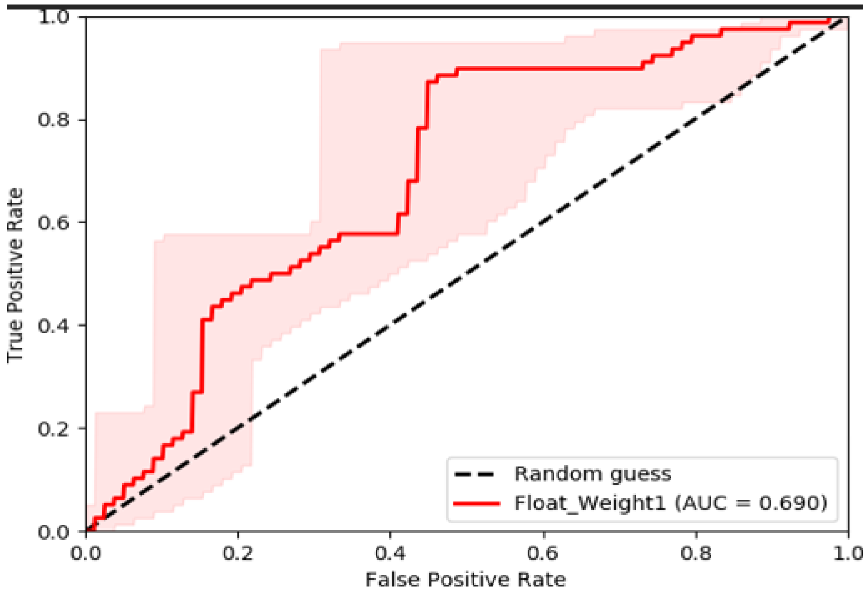

Fig. 5 AUC curve

LSM was evaluated to validate with ROC–AUC analysis. The values of the susceptibility map were assumed to be the false positive rate (FPR) in this process and the previous location of landslides in the district was the true positive rate (TPR). A graph was plotted between FPR and TPR and the resulting area under the curve indicated an overall model accuracy of 69%, reflecting a satisfactory predictive performance of the landslide susceptibility model. The success rate curve indicated good model reliability.

Results and Discussion

The landslide susceptibility zone map generated using AHP-GIS approach shows a clear delineation of Shimla district into areas with varying levels of susceptibility. The Shimla district is divided into five various categories of susceptibility namely very high, high, moderate, low and very low susceptibility. The specific regions shown by red colour on map are identified as regions highly susceptible to landslides. Also, the results indicate that the slope angle, geology and rainfall are the most influential and contributing factors in determining the landslide susceptibility regions in Shimla district. Wieczorek and Wilson (1996) classified significant triggering agents of landslides as rainfall, seismic forces and man-made interventions. Other factors, which include geology, rainfall and slope, have also been taken into consideration in this study with geology, rainfall and slope being the most operative factors. The findings are also found to have high correlation with the past landslide data that validates the success of the AHP-GIS methodology in the mapping of landslides. Guzzetti et al. (2005) furthered probabilistic hazard assessment techniques and emphasized the need to validate the techniques at the basin level. In this research, the strength of the applied methodology is proved by the fact that the susceptibility map coincides with historical landslide data.

These landslide susceptibility mapping findings have implications on land use planning, disaster risk management, infrastructure development, and other Government policies to Shimla district. Based on this study, the strengths of AHP-GIS methodology, which include flexibility, scaling and applicability to expertise knowledge, satellite data and field data, have been pointed out. Nonetheless, it has certain shortcomings including subjectivity of the AHP process and input data in GIS software may be even more finer. Pourghasemi, Mohammady, and Pradhan (2012) experimented with entropy and probability-based models of landslide. Their findings support the usefulness of GIS-based statistical integration that supplements the AHP-GIS method used in the Shimla district.

Landslide susceptibility map is a valuable instrument in the process of sustainable development as it helps a policy maker prioritize conservation and strong infrastructure at the high-risk area. This contributes to SDG 11.5 that targets to minimize the negative effects of disaster on the elderly population and SDG 13.1 that agrees on enhancing resiliency to natural disasters. According to Dai, Lee, and Ngai (2002), a worldwide perspective of landslide risk management was given, and there is a necessity to make the technical mapping meet with the decision making. This method is reflected in the current work which correlates the notions of susceptibility zonation and the sustainable development planning.

Table 3 shows that this landslide vulnerability mapping is aligned to some of the SDGs. It indicates the role of AHP-GIS methodology towards resilient infrastructure (SDG 9), disaster risk reduction (SDG 11), climate adaption (SDG 13), ecosystem protection (SDG 15) and collaborative governance (SDG 17). The table connects these technical outputs to the global sustainability goals by highlighting the wider societal and environmental effects of the study, the value of which is to foster safe, inclusive and sustainable development in landslide prone areas such as Shimla.

Table 3 Aligning of landslide susceptibility mapping and SDGs

SDG	SDG Target	Relevance to Study Outcomes	Key Contributions
SDG 9	Build resilient infrastructure	The susceptibility mapping of landslides helps in the locating roads, buildings and utilities in safer areas.	Promotes sustainable planning of infrastructure through minimizing the loss by landslides.
SDG 11	Reduce disaster impacts (Target 11.5)	Determines the high-risk areas to safeguard the neighborhoods and heritage (e.g., the tourism sites of Shimla).	Enables targeted disaster risk reduction (DRR) policies and resilient urban expansion.
SDG 13	Climate action (Target 13.1)	Addresses climate-induced landslides (e.g., rainfall-triggered slope failures).	Strengthens adaptive capacity to climate-related hazards in mountainous regions.
SDG 15	Protect terrestrial ecosystems	Reduces the causes of deforestation and soil erosion through conservation of potential vulnerable slopes.	Facilitates viable land-use in Himalayan ecosystems that are affected by landslides.
SDG 17	Multi-stakeholder partnerships	Combines GIS, AHP and expertise knowledge in the management of risks.	Shows the potential of technology and policy to be in line with sustainable development.

Conclusion

This study proves that Analytical Hierarchy Process (AHP) used with the Geographical Information System (GIS) is useful in mapping landslide susceptibility. It provides a strong scheme of landslide risk assessment and identification of at-risk areas. The study offers an end result landslide susceptibility map categorized into five levels of susceptibility of very high, high, moderate, low and very low. It demonstrates that the highest area of the Shimla district is exposed to moderate landslide susceptibility zone and then the low landslide susceptibility areas in the district. The northern part of the district shows very low landslide susceptibility due to constant slopes, undisturbed geology and mostly covered by snow and ice.

The results of this study are very important to local self-government and decentralized planning. The scientific evidence that the study offers by determining the area susceptible to landslides with accuracy can lead the local authorities, municipalities, and district administrations in Himachal Pradesh into safer land use planning, infrastructure development, and disaster management policies and strategies. The incorporation of GIS-based susceptibility mapping into the local governance systems enables the sub-national governments to make knowledgeable, data-driven decisions that are in line with the objectives of sustainable development and community resilience. In this regard, the current study can be added to the discussion on evidence-based local governance and local spatial planning that encourages the academic and practical knowledge of the local governance regimes across the world.

The study is useful to the decision makers and stakeholders in putting in place several disaster risk reduction measures, improvement of better land use planning as well as effective Government development policies and development plans. Zezere et al. (2008) provided the combination of economic cost analysis into probabilistic risk mapping demonstrating how hazard analysis can help in planning policies. On the same note, the current research paper emphasizes the need to align the susceptibility mapping with socio-economic priorities in Shimla. The development of the accuracy of the susceptibility map by using more detailed data and thematic layers on soil moisture content and seismic activities could be introduced in the range of future research. Also, this AHP-GIS method could be generalized to other regions under different geomorphological settings to confirm its applicability and the generalizability.

The influence of geospatial technologies on engineering sustainability and SDGs should also be mentioned in this research. The socio-economic data in the future can also be incorporated in the study so that landslide reduction measures are not biased and unfair towards anyone who strengthens global sustainable development agenda.

References

- A. K. Pachauri and M. Pant, "Landslide hazard mapping based on geological attributes," *Engineering Geology*, vol. 32, no. 1-2, pp. 81-100, 1992.
- Carrara, M. Cardinali, and F. Guzzetti, "GIS technology in mapping landslide hazard," in Geographical Information Systems in Assessing Natural Hazards, Dordrecht, Netherlands: Springer, 1995, pp. 135–175.
- D. J. Varnes, *Landslide Hazard Zonation: A Review of Principles and Practice*. Paris, France: UNESCO, 1984.
- E. J. Heikkila, *GIS-Based Multicriteria Decision Analysis: A Survey of the Literature*. New York, NY, USA: Springer, 2006.
- F. C. Dai, C. F. Lee, and Y. Y. Ngai, "Landslide risk assessment and management: An overview," Engineering Geology, vol. 64, no. 1, pp. 65–87, 2002.
- F. Guzzetti, P. Reichenbach, and M. Cardinali, "Probabilistic landslide hazard assessment at the basin scale," *Geomorphology*, vol. 72, no. 1-4, pp. 272-299, 2005.
- G. F. Wieczorek and R. C. Wilson, "Landslide triggering mechanisms," in Landslides: Investigation and Mitigation, Washington, DC, USA: National Academy Press, 1996, pp. 76–90.
- H. B. Pourghasemi, M. Mohammady, and B. Pradhan, "Landslide susceptibility mapping using index of entropy and conditional probability models in GIS: Safarood Basin, Iran," Catena, vol. 97, pp. 71–84, 2012.
- J. P. Van Westen, "GIS-based landslide susceptibility mapping: A case study in the Andes," *Geomorphology*, vol. 28, no. 3-4, pp. 345-358, 1999.
- J. R. Jensen, *Remote Sensing of the Environment: An Earth Resource Perspective*. Upper Saddle River, NJ, USA: Prentice Hall, 2000.

- J. van Westen, E. Castellanos, and S. L. Kuriakose, "Spatial data for landslide susceptibility, hazard, and vulnerability assessment: An overview," Engineering Geology, vol. 102, no. 3-4, pp. 112–131, 2008.
- K. C. Clarke, *Getting Started with Geographic Information Systems*. Upper Saddle River, NJ, USA: Prentice Hall, 2003.
- Kwan, J. S. H., & Chang, J. M. (2021). Landslide risk management for sustainable development.
- M. G. Anderson and K. S. Richards, *Slope Stability: Geotechnical Engineering and Geomorphology*. Chichester, UK: Wiley, 1987.
- M. L. Zêzere, R. A. C. Garcia, S. C. Oliveira, and E. Reis, "Probabilistic landslide risk analysis considering direct costs in the area north of Lisbon (Portugal)," Geomorphology, vol. 94, no. 3-4, pp. 467–495, 2008.
- Pradhan and S. Lee, "Delineation of landslide hazard areas using frequency ratio, logistic regression and artificial neural network model at Penang Island, Malaysia," Environmental Earth Sciences, vol. 60, no. 5, pp. 1037–1054, 2010.
- R. Anbalagan, "Landslide hazard evaluation and zonation mapping in mountainous terrain," *Engineering Geology*, vol. 32, no. 4, pp. 269-277, 1992.
- S. K. Sarkar and M. L. Gupta, Techniques of Landslide Hazard Zonation: A Review. Dehradun, India: Indian Institute of Remote Sensing, 2005.
- S. Lee and B. Pradhan, "Landslide hazard mapping at Selangor, Malaysia using frequency ratio and logistic regression models," Landslides, vol. 4, no. 1, pp. 33–41, 2007.
- T. L. Saaty, "Decision making with the analytic hierarchy process," International Journal of Services Sciences, vol. 1, no. 1, pp. 83–98, 2008.
- T. L. Saaty, *The Analytic Hierarchy Process*. New York, NY, USA: McGraw-Hill, 1980.
- United Nations. (2015). Transforming our world: the 2030 Agenda for Sustainable Development.