F.No. COE/ Ph.D/(Notification)/579/2025
Dated: 30-05-2025

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Title of Ph.D. Thesis: Climate Change Induced Landslide Susceptibility, Vulnerability and Risk Assessment: A Study of Shimla District, Himachal Pradesh

Keywords: Climate change; Landslide susceptibility; Landslide risk; Landslide vulnerability; Adaptation; Mitigation

FINDINGS

The thesis provided a comprehensive examination of climate change induced landslide susceptibility, vulnerability and risk in Shimla district, Himachal Pradesh. The study has explored susceptibility and different dimensions of vulnerability and risk to climate change-induced landslides and suggested effective adaptation and mitigation measures to lessen their implications. The analysis of rainfall trends revealed a statistically significant increasing trend annually and during the monsoon seasonal rainfall at the 95 per cent confidence level. In contrast, the summer, winter and post-monsoon seasons showed a declining trend in rainfall. A statistically significant increasing trend in annual and summer season for T max was observed at the rate of 0.12°C/year and 0.14°C/year, respectively. An increasing trend was observed for T min during the annual, winter, monsoon and post-monsoon seasons at the rate of 0.09°C/year, 0.02°C/year, 0.02°C/year and 0.03°C/year, respectively. The analysis of T mean revealed that summer, monsoon and post-monsoon seasons have noticed a warming trend that increases at the rate of 0.03°C/year, 0.01°C/year and 0.01°C/year, respectively. The seasonal forecasting using bagging-REPTree model further revealed an increasing trend in rainfall during the monsoon season by 731.04 per cent from 2022 to 2051 with an increase of 1.38 mm/year. Seasonal forecasting analysis observed an increasing trend in T max during the winter and monsoon seasons at the rate of 0.02°C/year and 0.07°C/year. During winter season, the T min and T mean forecasted an increase at the rate of 0.02°C/year and 5.04°C/year, respectively. The current trajectory of meteorological uncertainties, if continued, may disturb the ecological balance of the mountainous ecosystem and human well-being.

The analysis on landslide susceptibility revealed that the largest area of the district based on B-RF was found under the very high susceptibility zone (33.87 per cent) followed by the low (27.30 per cent), high (20.68 per cent) and moderate (18.16 per cent) susceptibility zones. Spatial analysis of landslide susceptibility revealed that blocks namely Basantpur, Rohru, Nankhari and Theog are susceptible to landslide. Abundant rainfall, steep slope, low NDVI, closer proximity to roads, fine loamy soil and strong earthquake magnitude have been identified as the major influencing factors for very high and high landslide susceptibility. High lineament density, complex lithology and moderate to high elevation have been attributed to moderate susceptibility. The key performance metrics and map validation

demonstrated that the B-RF model (correlation coefficient: 0.988, mean absolute error: 0.010, root mean square error: 0.058, relative absolute error: 2.964, ROC-AUC: 0.947, accuracy: 0.778, precision: 0.819, recall: 0.917 and F-1 score: 0.865) was the better-performing model. The assessment of landslide vulnerability and risk revealed that most of the area falls in a very high risk followed by high, low and moderate risk. Mashobra, Basantpur, Narkanda and Rampur blocks experienced very high landslide risk. Rainfall, slope, wetness index, building density and extensive road network have been attributed to very high landslide risk. Theog, Chaupal and Rohru blocks experienced high landslide risk. High temperature variability, high population density and low literacy rate have increased landslide risk in such blocks. Pearson correlation and hierarchical clustering analyses demonstrated that landslide risk was strongly correlated with the hazard and element-at-risk. In terms of conditioning parameters, mean annual temperature, rainfall intensity, accessibility of roads and railways, distance from school, marginalized population, illiteracy and non-cemented house have strong and positive correlation with landslide risk. Very high and high landslide risk blocks require attention of stakeholders for propelling slope stability measures, instrument installation and effective land use management.

Socio-economic characteristics and perception of the households regarding the impacts of climate change-induced landslides were ascertained through field work. The majority of the sampled households were characterized by low socio-economic status. Reaffirmation from the local communities also advocated a significant impact of climate change in terms of increased frequency of landslides during monsoon season. The internal resistance of house structure, availability of basic amenities, economic condition, social group, awareness level and land possession have significantly influenced adaptation and mitigation strategies in the district. Household-level assessment on landslide vulnerability worked effectively for understanding the implications for society and the environment. Wide variations were found in determining landslide vulnerability of the sampled households. The analysis revealed that high landslide vulnerability was found in Shakrori (0.28), Sarahan (0.27), Loharkoti (0.25), Nerua (0.22), Malendi (0.22), Malat (0.21), Anandpur (0.20), Jais (0.20) and Bahlun (0.20) villages. Residents reported high social vulnerability, high physical fragility and low implementation of adaptation strategies induced high composite landslide vulnerability. Regression analysis between composite landslide vulnerability index and its domains demonstrated that physical, economic and climate change and environmental domains were the most influential domains affecting landslide vulnerability. However, the early warning system, emergency response system and adaptation were found to have a negative association. In conclusion, this thesis seeks to bridge the gap between traditional climate trend analysis and the future forecasting of meteorological variables at the micro-scale. A concerted effort has been made in this study to assess landslide risk through a novel methodology that integrates hazard, vulnerability and elements-at-risk. The research holds significance as it synthesized various dimensions (social, economic, physical, environmental, early warning, emergency response and adaptation) to analyze household landslide vulnerability for devising site-specific adaptation and mitigation strategies in Shimla district.