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ORIGINAL PAPER

# Landslide susceptibility assessment of Kashmir Himalaya, India

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**Abstract**
Landslides are the most prevalent and recurrent natural hazard in the Kashmir Himalaya owing to its peculiar geological and topographic setting. Landslides adversely affect the socioeconomics of the region by causing huge loss of human life and infrastructure. In this study, two approaches: deterministic Stability Index Mapping (SINMAP) and semi-quantitative Multi-Criteria Evaluation (MCE) models were used to assess the landslide vulnerability of the Kashmir Himalaya. The two models combine fourteen different parameters related to topography, hydrology, soil, landuse/landcover, and internal frictional angle to determine the landslide susceptibility. SINMAP showed that ~ 55% (8648 $km^2$) of the area is landslide stable. Moderately and quasi-stable landslide classes together cover ~ 26% (4113 $km^2$) of the area. The unstable landslide class (threshold and defended) occupies ~ 18% (2823 $km^2$) of the area. MCE model indicated that ~ 40% (6311 $km^2$) of the area is stable, and ~ 31% (4832 $km^2$) of the area is under moderately and quasi-stable classes. The unstable landslide (threshold and defended) classes cover ~ 28% (4440 $km^2$) of the total area. The landslide susceptibility based on the two approaches showed a mismatch of ~ 42%. SINMAP and MCE showed an accuracy of 55% and 70%, respectively, using the receiver operator curve (ROC). To improve the accuracy of landslide susceptibility, the maps from the two approaches were combined using normalized frequency ratio (NFR) that enhanced the accuracy to 78%. The landslide susceptibility map generated in this study would help to generate a landslide mitigation plan to minimize the risks associated with the recurrent landslides observed in the region.

**Keywords** Landslide stability map (LSM) · Multi-Criteria Evaluation mode (MCE) · Stability Index Mapping (SINMAP) · Normalized frequency ratio (NFR) · Receiver operator curve (ROC)

## Introduction

Landslides in the Himalayas are very frequent mainly because of its intricate geo-tectonic setup, complex topography, and varied climatic setting (Saha et al. 2002; Chauhan et al. 2010; Sarkar et al. 2012; Singh et al. 2014a, b; Sangra et al. 2017). Globally, India ranks first, contributing 14.52%, in terms of fatal landslides in which the Northwest Himalayas, of which Jammu and Kashmir Himalaya are a part, contributes ~ 67% of the landslide, the Northeast Himalayas contributes ~19%, and the Western Ghats contributes ~ 15% (Froude and Petley 2018; Martha et al. 2021). Landslides cause significant loss of human life and severe damage to the infrastructure in the Himalayas (Naithani 2006; Haigh and Rawat 2011; Roslanl and Shafee 2011). The frequency of landslides in the region has increased over space and time due to the increased population (Kamp et al. 2008; Melanie et al. 2018), ecological unfriendly infrastructural development (Mahmood et al. 2017), land degradation (Zaz and Romshoo 2012; Romshoo et al. 2020), and deforestation (Rashid et al. 2011; Pham et al. 2018). From the last few years, the frequency of extreme weather events has increased due to changing climate that has triggered frequent floods, landslides, and avalanches in this region (IPCC 2001; Haigh and Rawat 2011; Hobley et al. 2012; Kumar et al. 2016; Romshoo et al. 2018; Zaz et al. 2019). Flash floods caused by landslides in river valley of the Himalayas have now become a frequent phenomenon. Such flash floods claim the lives of scores of people and cause huge loss to infrastructure ( Khan 2001; Sarkar et al. 2015). It has been projected that many regions in the south Asia may receive

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