Journal on Transportation System and Engineering
ISSN: 3059-9865(Print) 3059-9873(Online)
Vol. 1. Issue 2 (December) 2025: 76-83
DOI: https://doi.org/10.3126/jotse.v1i2.87759

Research Article
Received Date: Ma7 29, 2025
Revised Date: October 14, 2025
Accepted Date: November 16, 2025
Published Date: December 21,2025

Rainfall Threshold for Roadside Shallow Landslide in Mid-Himalayan Region of Nepal

Suresh Neupane[1], Netra Prasad Bhandari[2]

School of Science and Engineering, Special Graduate Course on Disaster Mitigation Study, Ehime University, Ehime, Japan.

2 Center for Disaster Management Informatics Research, School of Science and Engineering, Ehime University, Ehime, Japan. Email; - netra.prakash_bhandary.my@ehime-u.ac.jp>

Abstract

Nepal's road transportation infrastructure is primarily dependent on mountain routes, which are severely disrupted by rainfall induced landslides during the monsoon season. An early warning system based on a localized rainfall threshold is essential for disaster risk reduction because slope stabilization is expensive and road protection resources are scarce. This study uses intensity-duration methodologies and statistical analysis of historical rainfall data in the Mid-Himalayan region to ascertain the relationship between the occurrence of landslides and important triggering elements, including rainfall. For the roadside landslide in the Mid-Himalayan region, a local rainfall intensity-duration (I-D) threshold was determined by fitting a power-law equation obtained from 57 landslide events from 2017 to 2024, taking into account lower limitations delineated by quantile regression. The results show that there is a high chance of roadside landslides in the research area starting when there is 1.75 mm of rain per hour for 48 hours. The findings highlight the significance of cumulative antecedent rainfall in landslides and indicate that extended moderate rainfall (>72 hours) considerably adds to slope destabilization. The results show that July and August are the most dangerous months for roadside landslides, with the mid-Himalayan range experiencing the most rainfall and the high Himalayas seeing the least. By integrating this threshold into road infrastructure design and transportation management, authorities may improve disaster preparedness, give timely warnings, and reduce casualties, thereby boosting road network resilience in the mid-Himalaya region.

Keywords: Rainfall threshold; landslide early warning; intensity-duration relationship; climate change

1. Introduction

Among the most destructive geological hazards are landslides, which are especially dangerous in mountainous areas where they can seriously damage transportation networks, infrastructure, and human populations (Chen et al., 2015). Each year, they cause significant economic losses and fatalities, making them the second most consequential geohazard in the world (Azarafza et al., 2018). According to Aziz et al. (2024) and Komadja et al. (2021), landslides often cause extensive environmental damage, traffic disruptions, property loss, and human casualties in areas with delicate geology and heavy rainfall, like the Himalayas. Landslides frequently occur in the tectonically active Himalayan area and are mostly caused by steep slopes, fragile lithological formations, seismic activity, and heavy monsoonal precipitation (Kanungo & Sharma, 2014; Saha & Bera, 2024). More than 90% of rainfall-induced landslides in Nepal, in particular, occur during the monsoon season, which runs from June to September (Harvey et al., 2024). A combination of anthropogenic pressures and natural vulnerabilities increase the frequency and intensity of these catastrophes (Shrestha et al., 2019).

In Nepal's mid-Himalayan area, landslides brought on by rainfall present a serious threat to the road network. Because prolonged or intense rainfall raises pore water pressure and reduces the shear strength of soil materials, these landslides are typically shallow (0.5–2.5 meters deep), with slip surfaces parallel to the slope (Upreti, 1996; Dhital, 2018; Lepore et al., 2013). Several studies have used process-based hydrological models that incorporate soil moisture dynamics (Crozier, 1999) and empirical intensity-duration (I-D) models (e.g., Guzzetti et al., 2007; Caine, 1980) to determine rainfall thresholds for landslide start. I-D models provide useful regional guidance, but they frequently aren't able to capture the intricate subsurface factors that affect slope failure. However, despite its thoroughness,

Corresponding Author’s Email Address suresh.n2001@gmail.com

process-based models are less practical for widespread use and necessitate large datasets (Crosta & Frattini, 2017; Aleotti, 2004).

For the purpose of preparing early warning systems and improving catastrophe resilience, precise rainfall threshold estimation is essential, especially for traffic corridors that are vulnerable to slope failures. Different rainfall thresholds for landslide start have been identified by numerous research conducted throughout the Himalayan region. For example, Froehlich et al. (1990) found that shallow landslides might be caused by rainfall of 130–150 mm in a 24-hour period or 180–200 mm over three days in the Darjeeling Himalayas. Kanungo & Sharma (2014) confirmed similar findings in the Uttarakhand region, while Dahal & Hasegawa (2008) postulated an I-D threshold beyond which landslide risk considerably increases in the Nepal Himalaya. These findings highlight the necessity of setting location-specific thresholds that take into consideration regional variations in geology, rainfall patterns, and topography.

The mid-Himalayan region is particularly vulnerable due to its alternating dry and wet phases, with protracted monsoon spells and rare cloudbursts being common triggers for landslides (Harvey et al., 2024; Dahal & Hasegawa, 2008). Climate change is making extreme rainfall events more often, which emphasizes how urgent it is to set localized rainfall thresholds to improve disaster preparedness and infrastructure protection. This area frequently has roadside landslides, which seriously endanger life and property in addition to interfering with mobility. Early warning systems that are both affordable and locally relevant are essential in environments with limited resources.

The empirical relationship between rainfall features and landslide occurrences, specifically the minimal rainfall needed to trigger slope failures, has not been sufficiently characterized for the mid-Himalayan road networks, despite previous efforts. By creating a rainfall intensity-duration (I-D) threshold model based on historical rainfall and landslide data from the mid-Himalayan region and statistically analyzing past precipitation patterns to better understand their impact on landslide initiation and recurrence, this study seeks to close this gap.

2. Study Area

The Kanti Highway (H37), as shown in Figure 1(a), is a strategic road that runs 86 kilometers between Lalitpur Metropolitan City and Hetauda Sub-Metropolitan City. Originally built in 1954 and renamed in 1962 in honor of Queen Kanti, the highway currently serves as the quickest alternate route between Kathmandu and the Nepal-India border. Since its importance for trade and cross-border connectivity grew in the late 1990s, it was formally recognized as a crucial substitute for the Tribhuvan Highway. The 36-kilometer section between Thingan and Tikabhairab is especially vulnerable to shallow landslides brought on by monsoonal rainfall, despite the highway's vital significance. The Upper Siwalik and the Lesser Himalaya are the two main formations that make up the research area's geological framework, as depicted in Figure 1(b). About 4 km of immature, unconsolidated sedimentary rocks, including as mudstone, sandstone, siltstone, and conglomerate, make up the Upper Siwalik zone. These materials are highly weathered and friable, making them particularly vulnerable to erosion and landslide activity. Interbedded boulders and conglomerates, sandstone lenses, and sandy clays in various hues of yellow, brown, and grey are characteristics of the landslide-prone areas of this formation. During times of heavy monsoon rains, these units' mechanical fragility becomes crucial, frequently leading to slope failures.

On the other hand, the Lesser Himalaya, which takes up about 32 km of the highway corridor, is made up of a complicated series of sedimentary and metamorphic rocks that range in age from the Precambrian to the Eocene, including slate, phyllite, schist, quartzite, limestone, and dolomite. Because they are worn and foliated, phyllites are particularly vulnerable to sliding. The potential of instability along this section is further increased by karst-prone limestones and fractured quartzites.

The Lesser Himalayan region is home to three main geological groups:

- The Dadeldhura Group is made up of foliated rocks that allow for planar sliding, including granites, schists, and phyllites.
- The Kathmandu Group is distinguished by structurally distorted elements such as dolomite, quartzite, and limestone that have been considerably weakened by Himalayan tectonic processes.
- The Midland Group is made up of a variety of metamorphic and sedimentary rocks that are frequently broken up by granitic masses.

The Ipa Granite, which is close to Ipa Khola, is of special geological interest because of its coarse-grained texture and xenoliths, which provide even more complexity. This corridor is particularly susceptible to rainfall-induced landslides due to its steep terrain, brittle lithology, and active tectonics, which calls for ongoing monitoring and slope stability evaluation.

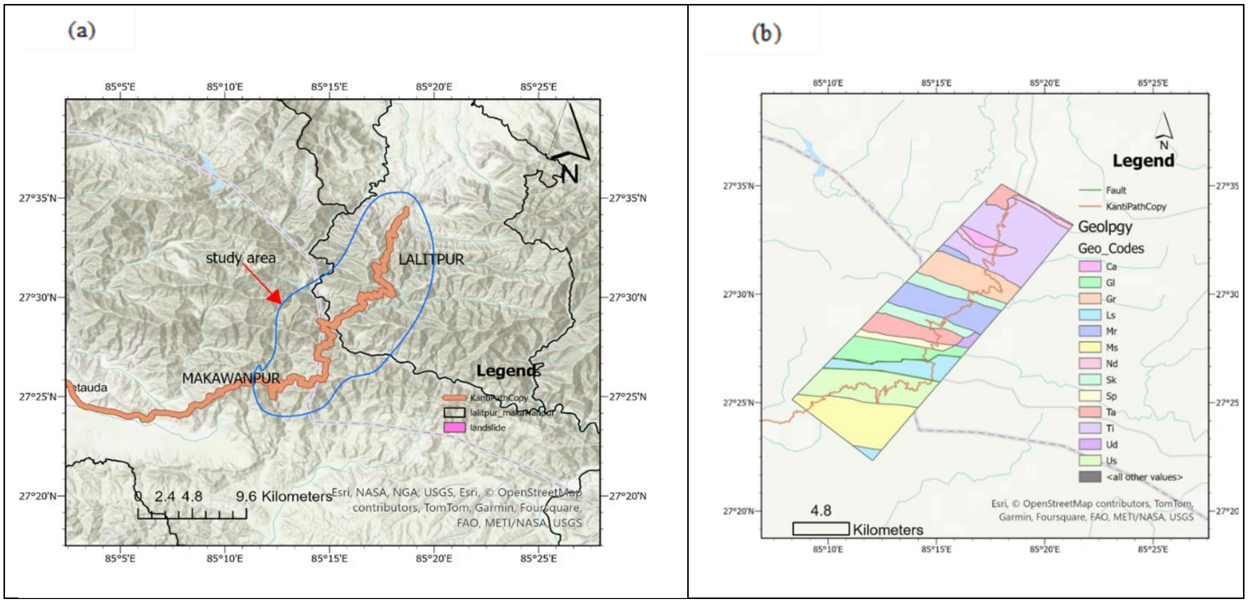

Figure 1: (a) Study area along the Kanti Highway(NH37) showing landslide locations and district boundaries, and (b) Geological map displaying fault and geological formations.

3. Methodology

A comprehensive empirical approach was adopted to establish a localized rainfall threshold for roadside shallow landslides in the mid-Himalayan region. This involves compiling landslide inventory data, analyzing long-term rainfall records, and applying statistical methods to build an empirical intensity–duration (I–D) threshold model.

3.1. Landslide Inventory D

For the years 2017–2024, a comprehensive inventory of 59 rainfall-induced landslides was compiled for the critical 36-km segment of the Kanti National Highway (Thingan–Tikabhairab) in Nepal's Mid-Himalayan region. The database was developed using multiple sources, including daily field reports from the Kanti Highway Project Office, maintenance logs, and personal field records of the first author (who served as Project Manager from 2021 to 2023). Each event was georeferenced and verified through GPS field surveys and cross-checked using Google Earth Pro imagery to ensure spatial accuracy and reliability. Only shallow translational and debris slides that directly affected roadway operations were considered in this analysis.

Among these, two events recorded at Chapagaun station during 2024 showed exceptionally high rainfall intensities (~7.9 mm/hr), corresponding to an extreme rainfall episode. These were statistically identified as outliers and therefore excluded from the regression analysis, though retained in the total landslide inventory count for completeness.

3.2 Rainfall Data Collection and Processing

Rainfall data for this study were obtained from the Department of Hydrology and Meteorology (DHM) of Nepal, which maintains a national network of meteorological stations. Within the study corridor, four nearest stations — Makwanpur Gadi, Lele, Chapagaun, and Khokana — were selected based on spatial proximity and record completeness. The dataset spans 35 years (1990–2024), with Lele and Khokana stations providing data from 1994 and 1992, respectively.

DHM records daily rainfall at 8:45 AM local time, representing the total precipitation for the preceding 24-hour period. For each documented landslide, event-based rainfall was extracted from the nearest station using spatial correlation in GIS. Since the available DHM dataset consists mainly of daily rainfall totals, a daily-to-hourly conversion was necessary to estimate shorter rainfall durations required for intensity–duration (I–D) analysis.

The empirical relationship developed by Shakya (2002), also adopted by Dahal and Hasegawa (2008), was applied to derive estimated rainfall for any duration (t, in hours) from the 24-hour recorded total (P_{24}, in mm), as shown in Equation (1):

$$\frac{P_t}{P_{24}} = sin\, sin\, \left(\frac{\pi t}{48}\right)^{0.4727} \qquad (1)$$

Where, P_t = estimated rainfall for the duration t (mm),
P_{24} = observed 24-hour total rainfall (mm).
This conversion allowed estimation of rainfall intensity (mm/hr) and duration (hr) for each landslide-triggering event when high-resolution (hourly) data were unavailable.
It is acknowledged that this method may introduce minor bias in intensity estimation because it assumes a uniform rainfall distribution within the 24 hours. However, it remains a practical and widely accepted approach in data-scarce Himalayan environments, enabling consistent comparison of rainfall thresholds across multiple stations and timeframes.

Subsequent statistical analyses were performed using Microsoft Excel and Python, employing descriptive statistics, pivot tables, and analytical libraries to assess spatio-temporal variability, seasonal distribution, and rainfall–landslide relationships within the study area.

3.3 Rainfall Intensity-Duration (I-D) Threshold Method

To define rainfall thresholds for landslide initiation, the intensity–duration (I–D) threshold method was applied—one of the most widely used empirical approaches in landslide hazard assessment (Guzzetti et al., 2007). Earlier studies (Caine, 1980; Chien-Yuan, 2005) relied on manual fitting techniques to determine threshold boundaries. However, recent advancements employ mathematical and statistical models for more objective estimation.

Among these, the quantile regression approach was chosen for its robustness in defining lower threshold boundaries in data-scarce environments. Additional methods referenced include Bayesian inference (Guzzetti et al., 2007) and frequentist analysis (Brunetti et al., 2010).

In this study, the rainfall threshold curve is modeled using a power-law relationship, expressed as:

$$I = \propto D^{-\beta} \qquad (2)$$

where I = rainfall intensity (mm/hr), D = duration (hr). α and β are empirical regression coefficients determined from curve fitting
A rainfall event was classified as landslide-triggering if the daily precipitation equaled or exceeded 2 mm, consistent with threshold standards adopted by ICIMOD and DHM. The rainfall event was considered to continue until the daily total dropped below this threshold. The event window, used to calculate the mean rainfall intensity and duration, varied based on site-specific conditions. To ensure accuracy, the nearest rainfall station to each landslide location was identified using GIS spatial analysis, facilitating precise correlation of meteorological data with recorded slope failure events.

4. **Results and Discussions**

4.1 Analysis of Rainfall Data

Analyzing rainfall patterns is crucial for water resource management, disaster preparedness, and landslide risk assessment in the mid-Himalayan region. The annual and monthly rainfall data from four meteorological stations, Makwanpur Gadi, Lele, Chapagaun, and Khokana were analyzed for the period 1990 to 2024, and the descriptive statistical analysis for annual rainfall was done and summarized in *Table 1*. Among the four stations, Makwanpur Gadi recorded the highest average annual rainfall of 2472.1 mm, with the maximum recorded in 1991 (3746.2 mm) and the minimum in 2010 (1221.4 mm). Lele station had an average annual rainfall of 1688.76 mm, with the highest in 2002 (2349.5 mm) and lowest in 2017 (1038.7 mm). Similarly, Chapagaun station recorded an average of 1304.88 mm, with the highest in 2011 (1758.9 mm) and the lowest in 2015 (771.2 mm). Khokana station showed an average of 1306.31 mm, with the maximum in 2002 (1941.2 mm) and the minimum in 2009 (889.6 mm).

Table 1: Descriptive statics for annual rainfall of the study area

Station	**Count**	**Mean**	**Percentage of Total Rainfall (PTR)**	**Minimum (Min)**	**Maximum (Max)**
Makwanpur Gadi	35	2472.11	37.79	1221.40	3746.20
Lele	31	1688.77	22.86	1038.70	2349.50
Chapagaun	35	1304.89	19.95	771.20	1758.90
Khokana	34	1306.31	19.40	889.60	1941.20
Total	135		100.00		

The monthly rainfall distribution for the study area is shown in *Table 2*, displays variations in monthly rainfall from 1990 to 2024 across four stations (Lele, Chapagaun, Khokana, and Makwanpur Gadi). The analysis indicates significant seasonal variation, with the highest rainfall occurring during the monsoon months (June–September) and the lowest rainfall observed in the winter months (November–February). Rainfall is minimal from January to May, with a gradual increase beginning in April. The peak rainfall occurs in July, which coincides with the monsoon season. After September, rainfall starts to decline, reaching its lowest levels in November and December. July experiences the maximum rainfall across all stations. The trends of maximum average monthly rainfall patterns show in decreasing order concerning station from Makwanpur Gadi (702.87 mm), Lele (479.36 mm), Chapagaun (367.71 mm), and Khokana (339.51 mm). Shrestha et al. (2012) studied the climate change and precipitation trend in Nepal and reported that monsoon rainfall has become more erratic, with intense but short-duration rainfall events increasing and observed higher rainfall in mid-Himalayan region. Rainfall shows significant fluctuations from year to year in the study area in 1993,2002,2013,2019 and 2024 the study area experienced higher than average rainfall, which is influenced by monsoon variability. Loo et al.(2015) examines the impact of climate change on monsoon seasonality and rainfall variability in Southeast Asia, highlighting a westward shift of the Indian summer monsoon and since the 1970s, increasing global temperatures have correlated with anomalous precipitation patterns, leading to intensified flooding, infrastructure damage, and food security risks in the region.

Table 2: Descriptive statics for average monthly rainfall data of the study area

Month	**Count**	**Mean**	**Percentage of Total Rainfall (PTR)**	**Minimum (Min)**	**Maximum (Max)**
Jan	35	19.40	1.14	0.00	82.51
Feb	35	23.46	1.38	0.00	93.68
Mar	35	30.24	1.78	0.00	84.65
Apr	35	54.53	3.20	0.93	125.55
May	35	125.21	7.35	52.90	241.28
June	35	254.98	14.97	78.68	548.53
Jul	35	474.43	27.85	242.87	950.98
Aug	35	403.60	23.69	264.85	621.53
Sep	35	241.53	14.18	105.95	513.92
Oct	35	61.77	3.63	4.00	219.35
Nov	35	5.04	0.30	0.00	68.80
Dec	35	9.34	0.55	0.00	120.70
Total	420	141.96	100.00	-	-

4.3 Rainfall Intensity – Duration (I-D) Thresholds

This study aims to estimate the rainfall thresholds that trigger roadside landslides in Nepal's Mid-Himalayan region, particularly along the Kanti Highway (H37). The mean rainfall intensity and corresponding duration for each landslide event were calculated using historical data from 2017 to 2024. For each landslide, the event onset was identified based on a daily rainfall of ≥ 2 mm, consistent with DHM and ICIMOD standards. Rainfall data from the nearest rain-gauge station to each landslide site were used to determine both rainfall intensity and duration. The resulting intensity–duration (I–D) values were plotted on a logarithmic scale, where the x-axis represents rainfall duration (hours) and the y-axis represents rainfall intensity (mm/hr). The observed rainfall intensity ranged from 0.5 to 3.8 mm/hr, with durations spanning 47.25 to 308 hours.

To determine the critical threshold boundary above which landslides are likely to occur, a 2nd-percentile quantile regression was applied to the dataset. This regression curve was fitted using a nonlinear power-law model in Python and is expressed as in Equation 3:

$$I = 19.37 * D^{-0.6215} \qquad (3)$$

Where, I= rainfall intensity (mm/hr.), and
D= rainfall duration (hours)

The regression line defines the lower-boundary threshold separating triggering and non-triggering rainfall events. The findings suggest that a rainfall intensity of about 19.37 mm/hr sustained for one hour or 1.75 mm/hr over 48 hours is sufficient to initiate slope failures, while rainfall below 1.10 mm/hr sustained for more than 100 hours can also induce landslides when antecedent moisture is high. Prolonged rainfall exceeding 12 days may trigger failures even under low-intensity conditions (> 0.55 mm/hr).

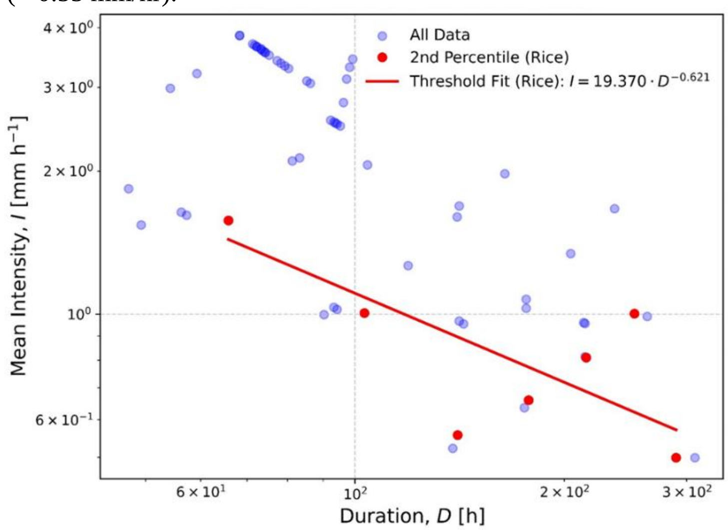

Figure 2: Rainfall intensity-duration scatter plot with 2nd percentile regression threshold curve for roadside landslide in mid-Himalayan region

These results highlight the dual influence of both short-duration, high-intensity and long-duration, low-intensity rainfall on slope instability. The quantile-regression approach applied in this study provides a more objective threshold estimation and reduces uncertainties common in data-scarce regions. The derived threshold ($I = 19.37 \times D^{-0.6215}$) is considerably lower than the regional threshold proposed by Dahal and Hasegawa (2008) for the Nepal Himalaya ($I = 73.90 \times D^{-0.79}$), but higher than the local threshold reported by Saha and Bera (2024) for the Garhwal Himalaya ($I = 1.38 \times D^{-0.126}$). This difference reflects the combined effect of the Mid-Himalayan corridor's more humid climate, moderate slope gradients, and prolonged monsoon episodes compared to the drier Garhwal region and the broader Nepal Himalaya averages.

While the limited number of data points introduces some uncertainty in defining the exact rainfall threshold, this can be minimized by incorporating additional rainfall events (Teja et al., 2019). The study emphasizes the importance of integrating local I–D thresholds with geological and hydrological factors to enhance the accuracy of landslide prediction and risk-assessment strategies for long-duration rainfall events.

4. Conclusion

This study presents an extensive overview of rainfall variability and its impact in inducing roadside landslides along the Kanti Highway (H37) in Nepal’s mid-Himalayan region. The study determines a region-specific rainfall intensity–duration (I–D) threshold for shallow landslides by combining long-term rainfall data (1990–2024) from four meteorological stations in the study area with a methodically assembled landslide inventory (2017–2024). The monsoon season, which occurs in July and August, contributes the most rainfall, according to descriptive statistical analysis, which also show significant interannual and seasonal variation. The Makwanpur Gadi station routinely had the highest yearly precipitation of all the stations examined, demonstrating the regional heterogeneity impacted by topography and climate.

The critical conditions for landslide occurrence are effectively characterized by the power-law relationship of the intensity–duration (I–D) threshold established in this study. The findings indicate that a rainfall intensity of 19.37 mm/hr sustained for one hour is sufficient to trigger slope failures. Similarly, prolonged rainfall events, such as 1.75 mm/hr over 48 hours or 0.55 mm/hr over 12 days, are also capable of inducing landslides in the study area. These threshold values highlight the dual influence of both short-duration, high-intensity and long-duration, low-intensity rainfall events on slope instability.

The results highlight the significance of combining I–D thresholds with geological, hydrological, and antecedent soil moisture conditions, even if the work admits several limitations, such as sample size restrictions and the lack of high-resolution hydro-meteorological data. Improving the precision of landslide prediction models requires this kind of integration. Overall, this study supports the use of multi-parameter early warning systems and emphasizes the critical role that localized rainfall thresholds play in determining landslide risk. In Nepal's mountainous areas, these insights are essential for improving the resilience of crucial transportation infrastructure and fortifying readiness for disasters.

5. References

Aleotti, P. (2004). A warning system for rainfall-induced shallow failures. *Engineering Geology*, *73*(3), 247–265. https://doi.org/10.1016/j.enggeo.2004.01.007

Azarafza, M., Ghazifard, A., Akgün, H., & Asghari-Kaljahi, E. (2018). Landslide susceptibility assessment of South Pars Special Zone, southwest Iran. *Environmental Earth Sciences*, *77*(24), 805. https://doi.org/10.1007/s12665-018-7978-1

Aziz, K., Mir, R. A., & Ansari, A. (2024). Precision modeling of slope stability for optimal landslide risk mitigation in Ramban road cut slopes, Jammu and Kashmir (J&K) India. *Modeling Earth Systems and Environment*, *10*(3), 3101–3117. https://doi.org/10.1007/s40808-023-01949-2

Brunetti, S., Rossi, M., Luciani, S. ., Valigi, D., Guzzetti, F., Maria, T., & Peruccacci. (2010). Rainfall thresholds for the possible occurrence of landslides in Italy. *Natural Hazards and Earth System Sciences*, *10*(3), 447–458. https://doi.org/10.5194/nhess-10-447-2010

Caine, N. (1980). The Rainfall Intensity: Duration Control of Shallow Landslides and Debris Flows. *Geografiska Annaler. Series A, Physical Geography*, *62*(1/2), 23. https://doi.org/10.2307/520449

Crosta, G., & Frattini, P. (2017). *Rainfall thresholds for triggering soil slips and debris flow*. *January 2001*.

Crozier, M. (1999). Prediction of rainfall-triggered landslides: a test of the Antecedent Water Status Model. *Earth Surface Processes and Landforms*, *24*(9), 825–833. https://doi.org/10.1002/(sici)1096-9837(199908)24:9<825::aid-esp14>3.0.co;2-m

Dahal, R. K., & Hasegawa, S. (2008). Representative rainfall thresholds for landslides in the Nepal Himalaya. *Geomorphology*, *100*(3–4), 429–443. https://doi.org/10.1016/j.geomorph.2008.01.014

Dhital, M. R. (2018). *Landslides and debris flows of 19-21 July 1993 in the Agra Khola watershed of Central Nepal*. *July 2000*. https://doi.org/10.3126/jngs.v21i0.32143

Guzzetti, F., Peruccacci, S., Rossi, M., & Stark, C. P. (2007). Rainfall thresholds for the initiation of landslides in central and southern Europe. *Meteorology and Atmospheric Physics*, *98*(3–4), 239–267. https://doi.org/10.1007/s00703-007-0262-7

Harvey, E. L., Kincey, M. E., Rosser, N. J., Gadtaula, A., Collins, E., Densmore, A. L., Dunant, A., Oven, K. J., Arrell, K., Basyal, G. K., Dhital, M. R., Robinson, T. R., Van Wyk de Vries, M., Paudyal, S., Pujara, D. S., & Shrestha, R. (2024). Review of landslide inventories for Nepal between 2010 and 2021 reveals data gaps in global landslide hotspot. *Natural Hazards*, *0123456789*. https://doi.org/10.1007/s11069-024-07013-1

Kanungo, D. P., & Sharma, S. (2014). Rainfall thresholds for prediction of shallow landslides around Chamoli-Joshimath region, Garhwal Himalayas, India. *Landslides*, *11*(4), 629–638. https://doi.org/10.1007/s10346-013-0438-9

Komadja, G. C., Pradhan, S. P., Oluwasegun, A. D., Roul, A. R., Stanislas, T. T., Laïbi, R. A., Adebayo, B., & Onwualu, A. P. (2021). Geotechnical and geological investigation of slope stability of a section of road cut debris-slopes along NH-7, Uttarakhand, India. *Results in Engineering*, *10*(April). https://doi.org/10.1016/j.rineng.2021.100227

Lepore, E., Noto, L., Sivandran, G., Bras, R. L., & Arnone, C. (2013). Physically based modeling of rainfall-triggered landslides: a case study in the Luquillo forest, Puerto Rico. *Hydrology and Earth System Sciences*, *17*(9), 3371–3387. https://doi.org/10.5194/hess-17-3371-2013

Loo, Y. Y., Billa, L., & Singh, A. (2015). Effect of climate change on seasonal monsoon in Asia and its impact on the variability of monsoon rainfall in Southeast Asia. In *Geoscience Frontiers* (Vol. 6, Issue 6, pp. 817–823). https://doi.org/10.1016/j.gsf.2014.02.009

Saha, S., & Bera, B. (2024). Rainfall threshold for prediction of shallow landslides in the Garhwal Himalaya, India. *Geosystems and Geoenvironment*, *3*(3), 100285. https://doi.org/10.1016/j.geogeo.2024.100285

Shrestha, U. B., Shrestha, A. M., Aryal, S., Shrestha, S., Gautam, M. S., & Ojha, H. (2019). Climate change in Nepal: a comprehensive analysis of instrumental data and people’s perceptions. *Climatic Change*, *154*(3–4), 315–334. https://doi.org/10.1007/s10584-019-02418-5

Teja, A., Satyam, N., Surya;, & Togaru, D. (2019). Determination of rainfall thresholds for landslide prediction using an algorithm-based approach: Case study in the Darjeeling Himalayas, India. *Geosciences*, *9*(7), 302-NA. https://doi.org/10.3390/geosciences9070302

Upreti, B. N. (1996). Stratigraphy of the western Nepal Lesser Himalaya: A synthesis. *Journal of Nepal Geological Society*, *13*(0 SE-Articles), 11–28. https://doi.org/10.3126/jngs.v13i0.32127